RESPONSE OF CANOLA, WHEAT AND PEA TO FOLIAR PHOSPHORUS FERTILIZATION IN THREE SASKATCHEWAN SOIL ZONES

A Thesis Submitted to the College of Graduate and Postdoctoral Studies in Partial Fulfillment of the Requirements for the Degree of Master of Science in the Department of Soil Science University of Saskatchewan Saskatoon

By Stephen R.E. Froese

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University of Saskatchewan

51 Campus Dr.

Saskatoon, Saskatchewan SK S7N 5A8 Canada

Or

Dean

College of Graduate and Postdoctoral Studies

University of Saskatchewan

116 Thorvaldson Building, 110 Science Place

Saskatoon, Saskatchewan S7N 5C9 Canada

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Head

Department of Soil Science

University of Saskatchewan

51 Campus Dr.

Saskatoon, Saskatchewan SK S7N 5A8 Canada

Or

Dean

College of Graduate and Postdoctoral Studies

University of Saskatchewan

116 Thorvaldson Building, 110 Science Place

Saskatoon, Saskatchewan S7N 5C9 Canada

ABSTRACT

As agricultural crop yields increase, greater amounts of phosphorus (P) are removed from soil in harvested plant material. As a result greater amounts of phosphorus fertilizers are required to maintain both crop yields and long-term soil fertility. However P fertilizer application practices must consider factors including high reactivity of P with soil constituents such as Ca which can render large proportions of soil applied P unavailable. As P is relatively immobile in the soil it must be placed near the seed for early crop access, but crops such as canola or pea are sensitive to injury from seed placed P. Foliar P fertilization can potentially address some of these limitations of soil applied P via the application of liquid P fertilizer to crop foliage, especially to address mid to late season P deficiency. This study evaluated the response (agronomic, nutritional, and environmental) to foliar mono-potassium phosphate (KH_2PO_4) fertilization of canola, pea and wheat grown in Brown, Dark Brown and Black soils in Saskatchewan. In a randomized complete block design (RCBD), each P fertilization treatment plot received equivalent P fertilizer rates of 20 kg P_2O_5 ha^{-1} with varying proportion of P applied as seed-placed mono-ammonium phosphate (MAP) versus foliar KH_2PO_4. The treatments were: 1) control with no added P; 2) 20 kg P_2O_5 ha^{-1} seed placed MAP; 3) 15 kg P_2O_5 ha^{-1} seed placed and 5 kg P_2O_5 ha^{-1} foliar applied; 4) 10 kg P_2O_5 ha^{-1} and 10 kg P_2O_5 ha^{-1} as seed placed and foliar applied P; 5) No seed-placed MAP with all 20 kg P_2O_5 ha^{-1} as foliar applied P. Foliar treatments were made prior to anthesis in controlled environment studies conducted with two soils (Echo and Krydor associations), and field studies with four soils (Echo, Krydor, Sutherland and Weyburn associations) in 2016 and 2017. Of the three crops, canola was the most responsive to foliar P fertilization in terms of yield and P uptake response, followed by wheat and pea. Pea showed little response to P fertilization in general, attributed to its ability to effectively scavenge soil reserves of P. Evidence of P uptake through canola and pea leaf material was observed, but foliar P application did not effectively balance off the yield lost by reduced rates of seed-placed MAP fertilizer. Foliar P fertilization at the rates applied in this study had limited effect on human nutritional value of the grain as assessed through effect on grain Zn, Fe and phytate concentrations. Furthermore, there were no large discernible impacts of proportion of P applied in foliar versus soil applied on the dissolved reactive inorganic P (DRP) measured in simulated snowmelt runoff from post-harvest soils in controlled environment and field studies. It is concluded that mid-season foliar P applications would be most suitable for a top up of P nutrition applied in small amounts under conditions of soil P deficiency rather than as a substitution for seed row applied P fertilizer. Foliar P fertilization may be most suitable for canola where P demands are high and amounts applied at seeding in the seed row may be limited by seed-row safety concerns.

S

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Dedication

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LIST OF ABBREVIATIONS

Adenosine triphosphate	ATP
Aluminum	Al
Analysis of variance	ANOVA
Aqueous	*aq*
Bushel	bu
Calcium	Ca
Calcium Carbonate	$CaCO_3$
Centimeter	cm
Day	d.
Deoxyribonucleic acid	DNA
Diammonium phosphate	DAP
Diethylenetriaminepentaacetic acid	DTPA
Dissolved reactive inorganic phosphorus	DRP
Electrical conductivity	EC
Ethylenediaminetetraacetic acid	EDTA
x proportion of foliar fertilizer applied as foliar P_2O_5 ha^{-1}	F(x)
Gram	g
Hectare	ha
Hours	hrs
Hydrochloric acid	HCl
Hydrogen peroxide	H_2O_2
Inorganic phosphorus	P_i
Iron	Fe
Kilogram	kg
Magnesium	Mg
Manganese	Mn
Microgram	µg
Milligram	mg
Minute	min
Modified Kelowna	MK
Molar	M
Monoammonium phosphate	MAP
Mono- potassium phosphate	KH_2PO_4
Nitrogen	N
Organic phosphorus	Po
Orthophosphate	Ortho
Oxygen	O_2
P-solubilizing bacteria	PSB
P-solubilizing fungi	PSF
Phosphate	PO_4^{3-}

Phosphoric acid	H_3PO_4
Phosphorus	P
Phosphorus fertilizer	P_2O_5
Phytic acid	PA
Pound	lb
Relative Humidity	RH
Saskatchewan	SK
Sodium bicarbonate	$NaHCO_3$
Seed placed	SP
Sodium hydroxide	NaOH
Sulfur	S
Sulfuric acid	H_2SO_4
Triethanolamine	TEA
Triple superphosphate	TSP
United States of America	USA
Zinc	Zn

1.0 INTRODUCTION

1.1 Phosphorus in Saskatchewan Crop Production

Good soil fertility management is vital to economic and environmental sustainability of cropping systems. As fertilizer becomes scarcer and costs increase, innovation in fertilizer application strategies to improve plant use efficiency are especially desirable. Phosphorus (P) is an essential plant nutrient that is particularly important in early stage establishment and growth of annual crops. It is one of the most limiting nutrients across the Canadian prairies (Grant 2001). Phosphorus (P) is needed for storage and transfer of energy produced by photosynthesis for growth and reproduction. Adequate soil P levels promote root growth and winter hardiness, stimulate tillering, and accelerate maturity (Havlin et al., 2014). Practically, a soil is P deficient as long as it continues to respond to added fertilizer and will remain deficient as long as nutrient removal by the crop continues to exceed nutrient input. Canola, pea and wheat are important crops in Saskatchewan. With ability to achieve higher yield potentials through crop breeding and development, more nutrients are removed in harvested grain requiring greater spring nutrient applications to meet subsequent crop demand.

The most common P fertilizer used in Saskatchewan is granular monoammonium phosphate (MAP) with common numeric designation 11-52-0, which is typically soil applied near the seed during seeding to promote early root growth, causing a '*pop-up'* effect as the crop establishes quickly and evenly (Saskatchewan Ministry of Agriculture Phosphorus in Crop Production Fact Sheet). Due to its low mobility in the soil, fertilizer P is most effectively applied in or near the seed row. However, close proximity of the P fertilizer to the seed limits the rate at which it can be applied before injury occurs due to the salt effect of the fertilizer. Crop sensitivity of different crops is another important consideration, as crops such as canola and pea are more sensitive to higher P rates in the seed-row compared to cereals like wheat. The desire to implement higher P fertilizer rates along with more widespread use of low disturbance seeding tools has increased interest in maximum safe rates of seed-placed fertilizer (Qian and Schoenau, 2010). In many prairie soils the lime content is high and fertilizer P may readily react with calcium carbonates ($CaCo_3$) and other ions like Magnesium (Mg), forming P compounds unavailable for plant growth (Grant et al., 2001). Other soil limiting factors include texture, pH, moisture and temperature that often limit plant recovery of soil applied P fertilizer to 10-30 % during season of application. However up to 100 % of this seed-placed P may be recovered throughout the next few cropping years (Selles et al., 2011). The low mobility and high retention of P fertilizer in the soil has been addressed through broadcast of higher P fertilizer rates to build soil P (Wiens, 2017). Use of coated P forms to increase seed-row tolerance to soil applied fertilizer (Qian and Schoenau, 2010) and foliar P fertilizers as a means to overcome concerns about seed-row tolerance and fixation of added P in soil (Green and Racz, 1999) are other approaches to addressing these limitations.

The balance of annual P input and removal can be altered in years when a crop with low growth and/or a low demand for P is grown, while application of higher amounts of P at the beginning of a season can compensate for years of high growth and/or a high P-demanding crop. However, when large amounts of P fertilizer are added that greatly exceed the crop removal over a number of years, especially when broadcast, concerns surrounding export of P in run-off and contribution to waterbody eutrophication arise (Morales-Marin et al., 2017; Ulrich et al., 2016; Wiens, 2017). Eutrophication is the nutrient enrichment of water bodies and has long been associated with agricultural fertilizer inputs that in some regions can account for over 90 % of P inputs into eutrophied water bodies (Newman, 1995). Phosphorus from manure or synthetic fertilizer stratified at the soil surface can be exported from fields in excess rain or snowmelt water running off the field into rivers, streams and lakes. Previous research has found rates of 20 kg P_20_5 ha^{-1} of broadcast un-incorporated P fertilizer and seed-placed P to have little difference in dissolved reactive inorganic P (DRP) in snowmelt water runoff and leachate (Wiens, 2017). However, higher rates of broadcast P (80 kg P_20_5 ha^{-1}) without incorporation greatly increased the export of DRP in snowmelt run-off water, with the degree of P recovery by the crop dependent on crop type (Weiseth, 2015; Wiens, 2017). Mid or late-season P fertilizer applications may be beneficial in meeting additional crop needs for P apart from that supplied at seeding. Applications of P fertilizer to the foliage of a crop may have benefits as a means of topping up P nutrition and avoiding fixation in soil. Foliar applied P fertilizer that is not intercepted by the crop and reaches the soil may also be utilized by the crop but could also experience greater run-off losses. This thesis work examines the effectiveness of foliar P fertilization as a P fertilizer application strategy to supply all or a portion of the fertilizer P requirement of a crop, specifically canola, pea and wheat.

1.2 Foliar Phosphorus Fertilization

Foliar fertilization dates back to the 19^{th} century (Gris, 1843) and since then, the concept of nutrient uptake through leaves has received considerable attention (Fernandez et al., 2013; Kannan, 2010; Noack et al., 2010). Foliar fertilizers are aqueous solutions typically comprised of dissolved mineral element compounds (usually salts) and other components such as surfactants and wetting agents that are applied to the leaf material of a crop. The main rationale for foliar fertilization is to consider foliar fertilization when: 1) soil conditions limit availability of soil applied nutrients, 2) high losses of soil applied nutrients are anticipated, 3) plant growth stage, demand and environmental conditions interact to limit nutrient uptake (Fernandez et al., 2013). While more common in fruit production, there has been an industry promotion of foliar P application for prairie farmers largely based on results from other regions of the world; for example on wheat, corn and soybean in the US and India (e.g. Elliot et al., 1997; Ling and Silberbush, 2007). More recent research involving foliar P application to crops, predominantly on wheat, has included regions such as Europe, China, and Australia, (Jarecki et al., 2017; McBeath et al., 2011; Staugaitis et al., 2017; Wang et al., 2017;). Foliar P application has been recommended as a remedy for stress, however there is not an abundance of literature on the mechanisms that are associated with uptake and response. High rates of foliar phosphate have been reported to have a positive effect on winter wheat productivity under unfavourable conditions such as excess moisture or low temperature stress (Kostadinova et al., 2015). Studies on timing of application have revealed mixed responses. Post-anthesis application marginally increased yield with increased grain fill (Benbella and Paulsen, 1998; Gray, 1977). In wheat, the most effective time of application is believed to be before anthesis (Batten et al., 1986; Mosali et al., 2006; Rose et al., 2007) to improve tiller production. The greatest benefits were observed under low moisture and highly P-deficient soil conditions. Previous research suggests that soil applied P at seeding supplemented with foliar P application can increase crop yield and quality (Green, and Racz, 1999; Ling and Silberbush, 2007; McBeath et al., 2011; Mosali et al., 2006). Green and Racz (1999), in Manitoba reported marked increases in winter wheat yields with use of foliar P application suggesting foliar P fertilizer as a potentially viable option to increase grain yields under Canadian Prairie conditions. Outside of a P deficient soil, there are many environmental, biological and physiological factors affecting plant response to foliar spray: leaf age, leaf surface, leaf ontogeny, leaf homogeneity, canopy development, light, temperature, humidity, plant species and variety (Fernandez et al., 2013). Stomata have been observed to contribute to the foliar absorption process (Eichert and Burkhardt, 2001; Eichert and Goldbach, 2008). Efficacy is also dependent on the foliar solution regarding its concentration, solubility, solution pH, molecular weight, electrical charge, point of deliquescence and additional adjuvants (Fernandez et al., 2013). As Saskatchewan producers grow increasingly interested in improving agronomic efficiency, it is necessary to evaluate methods of addressing P deficiency while minimizing practices that lead to buildup of soil P susceptible to export in water runoff.

1.3 Seed Phosphorus Content

Within the seed, P is primarily stored as phytic acid (PA) that accumulates in protein vacuoles located in the aleurone layer of wheat. Phytic acid (PA) comprises up to 80 % of total seed P and can comprise as much as 1.5 % of seed dry weight (Bohn et al., 2008). It is considered an anti-nutrient due to its ability to bind to minerals such as calcium (Ca), potassium (K), zinc (Zn), iron (Fe), manganese (Mn) and Mg, rendering them unavailable for human digestion and nutritional non-factors (Bohn et al., 2008). However, the impact of soil application versus foliar application of P on seed phytate content is not known. Zinc and Fe are essential micronutrients in human health and deficiencies are a significant health concern in several human populations throughout the world. Zinc and Fe concentrations in the plant are positively correlated (Bohn et al., 2008), however Zn and P have been shown to be negatively correlated and P induced Zn deficiency has been attributed to P fertilizer application made in Zn deficient soils (Soltangheisi et al., 2014). This relationship could be a result of a reaction or antagonism in the soil or some interference in transport of Zn from soil to shoot. High rates of P fertilizers reduce Zn translocation to the shoot (Novais et al., 2016), which may decrease concentration of Zn in the seed. On the other hand, Zn fertilizers have been found to only reduce P availability from fertilizer P sources and not soil P (Soltangheisi et al., 2014). Foliar P application that provides P directly to the shoot and leaves may address plant P deficiency without interfering with soil Zn uptake or translocation to the shoots.

1.4 Justification of Research

There has been little research on foliar P application conducted on crops grown in prairie soils. The agricultural landscape of Saskatchewan is dominated by Chernozemic soils typically associated with enriched organic matter content in the surface (A) horizon and neutral to alkaline pH. These soils can be associated with high free lime ($CaCO_3$) content, especially in the drier regions where less leaching occurs. Research work has been conducted outside Canada and has reported some benefits from foliar P in primarily horticultural crops and some agricultural crops. Information is needed on agronomic and environmental implications of including foliar P fertilization as an application strategy for small grains including canola, pea and wheat on the prairies. Few if any studies have evaluated the efficiency and fate of foliar applied P fertilizers under western Canadian conditions in the field. The reason for the growth chamber studies was to evaluate the effect of foliar P treatment under controlled conditions using soil that was taken from the control treatments of the field study described previously, and to assess P uptake in a closed system. Research described in this thesis addresses this gap.

1.5 Hypothesis and Objectives

The hypotheses addressed in this research were as follows:

1. Crops that receive a combination of soil-applied and foliar P will produce higher yield than crops that receive all of the P applied as a foliar or soil treatments. Response to foliar P will be limited by the capacity of the leaves to absorb and retain P ions.
2. Addition of P in foliar form will not significantly affect seed Zn, Fe or phytate content.
3. A proportion of P added via foliar application will promote recovery of P fertilizer in harvested grain.
4. Foliar P application will not reduce P runoff versus soil application. Phosphorus (P) that is not absorbed by the leaves will accumulate in the soil.

The general goal of the research was to determine the crop and soil response to foliar applied P fertilizer that is applied alone, and in combination with soil applied P.

Specific objectives were:

Determine the effect of different proportions of soil versus foliar applied P on crop (canola, wheat, and pea) response (yield, nutrient uptake and composition) and residual soil P fertility at different locations in Saskatchewan with contrasting soil and environmental conditions.

Evaluate how foliar P fertilization affects potential loss of P from the soil in simulated snowmelt run-off.

1.6 Thesis Layout and Organization

The thesis organization is manuscript style, with introduction, general literature review, two research chapters covering the thesis work, and a general thesis research synthesis and conclusion. The first research chapter emphasizes agronomic impacts, covering the effects of foliar versus soil applied P on crop yield, P uptake and seed micronutrient and phytate content. The second chapter deals with environmental implications, specifically the impact of foliar versus soil application on P export in simulated snowmelt run-off. Growth chamber studies were used to evaluate treatment effects under controlled conditions with minimal confounding factors where effects are more easily and consistently revealed, with subsequent evaluations made under actual field conditions in farm field settings to verify the controlled environment studies and provide results that are most relevant to growers.

2.0 Literature Review

2.1. Soil Phosphorus Forms

Soil P exists in both organic and inorganic chemical forms, the species of which occur in complex equilibria with each other ranging from stable, sparingly available, to plant available labile and solution P pools (Shen et al., 2011). Organic P makes approximately 30% to 65% of total soil P, while inorganic P comprises 35% to 75% of total soil P and exists in both primary and secondary P minerals adsorbed to clays, carbonate minerals, and oxides (Harrison, 1987). Soil properties and climatic conditions affect the availability of soil P and crop response to P fertilizers. Climatic conditions such as precipitation, temperature, moisture, soil aeration and salinity influence the rate of P mineralization from decomposing organic matter.

A range of adsorption/desorption and precipitation/dissolution reactions control inorganic P mobility and bioavailability (Hinsinger, 2001). Primary P minerals, (apatite, strength and variscite) are stable in the soil and rely on dissolution via weathering to release available P. This process, however, is slow and typically unable to meet crop demand. Secondary P minerals include Ca, Fe and aluminium (Al) phosphates. These minerals dissolve and precipitate, cycling P back and forth between the available and unavailable pools. The dissolution rates of these minerals vary depending on the size of the mineral particle, ionic P concentration, soil pH, anions competing with P ions for ligand exchange, and concentration of metals that co-precipitate with P (Ca, Fe, and Al) (Hinsinger, 2001; Pierzynski et al., 2005). Inorganic P also exists adsorbed to clays, Fe and Al oxides which is made available via desorption reactions. Soil pH influences orthophosphate fixation to Al, Fe and Ca. Soils with pH values between 6 and 7.5 promote P availability while values below 5.5 and above 7.5 limit P availability. With increasing soil pH, the solubility of Fe and Al phosphates increases but the solubility of Ca-phosphates decreases, with the exception for pH values greater than 8 (Hinsinger, 2001). Many of the soils in the agricultural region of Saskatchewan developed under grasslands are slightly basic Chernozems in which $H_2PO_4^-$ readily precipitates with Ca into slightly soluble Ca salts. In acidic soils, P is predominantly adsorbed to the surface of clay minerals, Al and Fe oxides and hydroxides as they have large specific surface areas providing many adsorption sites. Adsorption is increased with increasing ionic strength. Soil P may also be bound in nano-pores in Fe/Al oxides becoming unavailable (Arai and Sparks, 2007). In calcareous soils, P is retained primarily by precipitation with Ca, forming plant available dicalcium phosphate as the initial reaction product (Shen et al., 2011). Dicalcium phosphate can further be transformed over time into more stable forms such as octocalcium phosphate and hydroxyapatite (HAP), which are less available at alkaline pH (Arai and Sparks, 2007).

2.1.1 Phosphorus fertilization of crops in Saskatchewan

2.1.1.1 *Application strategy*

Nutrient rate recommendations for P fertilization are based on meeting crop P requirement in the season of application (sufficiency) and replacing harvest export of P over the long term (maintenance). They are often chosen based on soil and plant tissue tests taken for current and future growing seasons. According to the Government of Saskatchewan (Saskatchewan Ministry of Agriculture Phosphorus in Crop Production Fact Sheet), total P uptake (above-ground) for pea is 0.76-0.92 lb. P_2O_5 bu^{-1} in a 50 bu $acre^{-1}$ yielding crop, canola is 1.31-1.63 lb. P_2O_5 bu^{-1} for a 35 bu $acre^{-1}$ crop, and wheat is 0.73-0.88 lb. P_2O_5 bu^{-1} for a 40 bu $acre^{-1}$ crop. In western Canada, P fertilizer is predominantly placed in the seed-row or banded, typically in the form of monammonium phosphate (MAP). Seed-row placed fertilizer rates are limited by the salt tolerance of the seed. Phosphorus (P) based fertilizers are often recommended as part of starter fertilizer blends to be placed in the seed-row to enable annual crops early access to P following germination. Due to its low mobility, P uptake is greatly influenced by P distribution and root density (Shenk and Barber, 1979). Generally it is considered beneficial to place P fertilizer in the soil compared to broadcasting, in order to enhance root uptake and P fertilizer use efficiency, and also minimizes losses of P in the run-off water (Weiseth, 2015). However, a study by Barbieri et al. (2014), wheat in Argentina showed no difference in crop recovery and yield response between banding and broadcast applications. However the location of this experiment (Argentinian Pampas) does not reflect soil, temperature, and moisture conditions like Saskatchewan. In Saskatchewan, cold soil temperatures are problematic as they inhibit P diffusion and early root growth. Generally it is considered that for lower of application of P fertilizer, the most effective method of application to meet plant P requirement in Saskatchewan is seed-placed (SMA Fact Sheet P Fertilization in Crop Production).

2.1.1.2 *Phosphorus fertilizer sources*

There are numerous dry and liquid P fertilizer formulations available to producers and more continue to be released to the market each year. Common P fertilizer forms worldwide re monoammonium phosphate (MAP) (11-52-0), ammonium polyphosphate $(10\text{-}34\text{-}0)_{aq}$, triple superphosphate (TSP) (0-46-0), and diammonium phosphate (DAP) (18-46-0) (Havlin et al.

2014).Research has been done comparing dry formulations versus liquid (e.g.: Lombi et al., 2003, McBeath et al., 2007, , Tunesi et al., 1999). Liquid and granular fertilizers are generally equally effective in slightly acid to alkaline soil (pH: 5.2-8.9) in regards to dry matter production. However, in a study with wheat in Australia, liquid fertilizer application produced greater plant response compared to granular P in calcareous soils, with improved response as the amount of $CaCO_3$ increased (McBeath et al., 2007). Bertrand et al., (2006) evaluated powdered MAP, DAP and TSP in comparison to liquid MAP, DAP and phosphoric acid (H_3PO_4) in four alkaline soils in Australia: grey calcareous, red calcareous, vertisol and sodisol soil types. It was found that a larger portion of the dry P products had been fixed into forms unavailable for plant uptake compared to the liquid formulations. Holloway (2001) banded liquid N, P and Zn mixes in grey and red calcareous soils and found aqueous P resulted in higher dry shoot weight, grain yield and P uptake than granular forms. The liquid P at 8 kg ha^{-1} produced 22% - 27% more grain than granular fertilizer. Alkaline and or calcareous soils have reduced P uptake as a result of rapid P fixation into sparingly soluble forms unavailable to the plant (Bertrand et al., 2006). Phosphorus (P) is heterogeneously distributed through the soil and is more likely to interact with Ca than Fe in calcareous soils (Lombi et al., 2006). A study of long-term fertilized P-rich soil, found Ca phosphates to be the dominant precipitate at pH 7.4-7.6 (Beauchemin et al., 2003). Lombi et al., (2005) found over a five week period between 9.5% and 18% of P applied as granules did not diffuse from the dissolution site into the surrounding soil regardless of soil type. Phosphorus (P) applied as liquid however proved to be significantly more soluble in calcareous soil resulting in a higher diffusion rate.

Phosphorus (P) behaviour was noted to be independent of form (liquid versus granular) in non-calcareous alkaline soils (Lombi et al., 2005). The dissolution of dry P fertilizer outwards is limited in calcareous soil as localized areas with high amounts of P precipitate into insoluble Ca-P (Bertrand et al., 2006). The isotopic exchangeability of liquid P was greater than dry P. The eventual precipitation of P into Ca-P and apatite-like insoluble compounds that decreases P availability was less prominent with liquid P as it was reported to remain in a form similar to monocalcium phosphate (Lombi et al., 2006).

2.1.2 Plant phosphorus uptake

Plant available P occurs as orthophosphate ($H_2PO_4^-$ and HPO_4^{-2}) in the soil solution and is absorbed through high-affinity active transport systems in the root or through a mycorrhizal dependant pathway (Shen et al., 2011). Phosphorus (P) uptake can be further supplemented by soil and rhizosphere P-solubilizing bacteria and fungi which promote plant growth (Richardson et al., 2009). Phosphorus (P) solubilizing microorganisms account for 1% - 50% of P-solubilization potential (Chen et al., 2006). Roots are able to change the chemical and biological characteristics of the rhizosphere to increase the bioavailability of soil P. In alkaline conditions, protons released by the root acidify the rhizosphere; this acidification can decrease the rhizosphere pH by 2 to 3 units (relative to bulk soil) allowing dissolution of sparingly available P (Marschner, 1995). Legumes such as pea are particularly effective P scavengers in calcareous soils. The exudation of carboxylates such as citrate, malate and oxalate mobilize sparingly available P via chelation and ligand exchange (Hinsinger et al., 2005). Root exudation of enzymes such as phosphatase or phytase mobilize organic P through hydrolysis (Zhang et al., 2010). However, interactions between soil microorganisms, pH, and availability of substrate and root exudates can inhibit P uptake; carboxylates may interact strongly with soil particles causing low P mobilization (Shen et al., 2011).

2.2 Foliar Phosphorus as an Application Strategy

2.2.1 Uptake pathways of foliar fertilizer

Plant leaf material is reported to be well adapted to mediate the transport of water vapour and gases, minimize the loss of nutrients, metabolites and water under adverse environmental conditions (Fernandez et al., 2013). Leaf tissue is covered by a waxy hydrophobic cuticle fitted with modified epidermal trichome or stomatal cells, and the degree of plant surface hydrophobicity and polarity is largely influenced by plant species and chemistry (Fernandez et al., 2013). Wheat has been characterized as having a crystalline wax structure and trichomes which increase leaf surface water repellence (Holloway, 1993), in addition, increasing trichome density reduces water retention and creates a physical barrier between solution and plant cuticle (Pierce et al., 2014). The penetration of solutes into leaf tissue is a passive process controlled by concentration gradients described by Fick's law, in which the rate of diffusion of any plant surface-applied solute through the leaf is dependent on its concentration both on the surface of and inside the leaf (Fernandez and Eichert, 2009).

Plant means for importing foliar applied nutrient solutions include cuticular penetration, uptake and absorption into metabolically active cells in the leaf, followed by translocation and utilization of nutrients by the plant (Fernandez et al., 2013). Foliar P fertilizer uptake can occur through stomatal pathway and non-stomatal pathway. However, it is not well established which pathway is more significant (Buick et al., 1992; Kirkwood, 1999; Oosterhuis, 2009). Uptake through stomata is limited by light, temperature and water stress (Currier and Dybing, 1959; Eddings and Brown, 1967; Sargent and Blackmon, 1965). Greater stomatal abundance has been correlated with greater foliar uptake (Eichert and Goldbach, 2008; Schonherr and Bukovac, 1978), however factors such as leaf venation and wax morphology make it difficult to determine the individual contribution of the stomata (Pierce et al., 2014). Solutes have been suggested to penetrate the stomata by diffusing along the pore walls that are seemingly less size selective than the cuticle (Eichert et al., 2008). In wheat, stomata are more abundant on the adaxial (upper) side of the leaf and despite higher trichome density and greater hydrophobicity on this side, foliar P recovery in relation to stomatal densities and leaf wettability suggest the stomata to be the major pathway of leaf uptake (Pierce et al., 2014).

Non-stomatal uptake occurs through negatively charged pores in the waxy leaf cuticle where net negative charge repels anionic P formulations (Tyree et al., 1990) and allows the phosphate to pass through. The structure and chemical composition of the cuticle varies with environmental and physiological conditions during growth and development (Dominguez et al., 2011; Fernandez and Brown, 2013; Kosma et al., 2009), and is an effective barrier preventing both water loss and penetration of foliar applied chemicals (Fernandez et al., 2013). Environmental factors such as relative humidity (RH) have been seen to influence leaf wax morphology in which *Brassica oleracea* grown at low RH (20 – 30 %) increased leaf surface wax deposition and crystal density (Koch et al., 2006). The hydrophobic and lipophilic structure of the cuticle limits diffusion of polar, hydrophilic compounds, however at high rates hydrophilic and polar compounds may penetrate the cuticle (Fernandez and Eichert, 2009). Nonionic solutes diffuse across a chemical potential gradient driven by concentration inside and outside the leaf, while a second, electrical potential gradient is involved in the penetration of ions like phosphate which is driven by charges of permeating ions (Fernandez and Eichert 2009). In this case, when anions and cations are imported at different rates a charge imbalance is caused, creating an electrical potential gradient which can be a primary driving force of ion movement and even against a concentration gradient (Tyree et al., 1990). A net negatively charged cuticle repels anions prompting preferential penetration of cations over anions (Tyree et al, 1990) which increases the electrical potential difference to a point where the electrical potential difference counterbalances the opposite directed chemical potential difference (Fernandez and Eichert 2009; Riederer, 1989). Charge balance can be restored by cations and anions diffusing together (symport) in which cation penetration rate is governed by the slower, limiting penetration rate of the anion, and or by export (antiport) of cations (likely Ca and Na) in which cation exchange is independent of the anion (Fernandez and Eichert, 2009; Heredia and Benavente, 1991). It has been suggested that the rate penetration of solutes determined experimentally is too high to be attributed to cuticular dissolution and diffusion and that hydrophilic solutes may penetrate the cuticle through polar, aqueous pores (Schonherr, 2006; Schreiber, 2005; Schreiber and Schonherr, 2009).

2.2.2 Plant phosphorus translocation

Phosphorus (P) uptake occurs throughout the plant life cycle until physiological maturity (Batten et al., 1992) and in the plant, P is highly phloem mobile compared to conditionally mobile Zn and Fe and therefore more likely to stimulate systemic response as opposed to local response (Marshner, 2012). The leaf apoplast participates in ion exchange and acts as a diffusion barrier which may accumulate cations and repel anions (Sattelmacher, 2001; Speer and Kaiser, 1991; White and Broadley, 2011) and a higher degree of polar and hydrogen-bonding interactions with water and solutes can be expected in the leaf apoplast than the cuticle (Fernandez and Brown, 2013). Leaf developmental stage plays a significant role in nutrient translocation in which immature leaves are incapable of exporting nutrients and are dependent on imported assimilate, whereas mature leaves are incapable of importing nutrients and become source organs that export nutrients like P to other plant organs (Fernandez and Brown, 2013). Plant P remobilization ability is also influenced by genotype, soil P level, environment (moisture, temperature, and salinity) and population density (Dordas, 2009). During grain development, there is significant P translocation from the leaf and stem tissue to the head rather than further soil P uptake (Batten et al., 1986; Grant et al., 2001; Papakosta, 1994). At maturity, 70 – 90% of total plant P resides in the seed of cereal and legume crops (Batten et al., 1986), while only a small fraction of applied fertilizer P is translocated to and retained in wheat chaff fractions (McBeath et al., 2011).

2.2.3 Agronomic responses to foliar phosphorus

There have been numerous studies evaluating foliar P efficacy conducted around the globe however few have been conducted on the Canadian Praires. Table 2.1 briefly summarizes some previous foliar P research conducted around the world under different growing conditions as well as fertilizer source.

Table 2.1: Previous research on foliar P application at diverse locations with different crops and P sources.

Location	Crop	Foliar P Source	Conditions	Citation
China	Winter wheat	KH_2PO_4, monosodium orthophosphate	Field	Lv et al., 2017
China	Winter Wheat	KH_2PO_4	Field	Wang et al., 2015
South Australia	Wheat	H_3PO_4	Glasshouse	Pierce et al., 2014
United States	Winter Wheat	KH_2PO_4	Field	Mosali et al. 2006
Canadian Prairies	Spring Wheat	7:6:7 foliar solution	Field	Green and Racz, 1993
South Australia	Wheat	Ammonium polyphosphate, H_3PO_4	Glasshouse	McBeath et al., 2011

Saudi Arabia	Wheat	Diammonium phosphate	Field	Al Harabi, et al., 2013
India	Soybean	BOOST-52 (0:52:34)	Field	Garud et al., 2015

Foliar P fertilization has produced mixed results regarding its value in agricultural cropping. However under adverse climatic conditions the input of pre-anthesis assimilates might be useful for maintaining grain yield (Arduini et al., 2006). In wheat, foliar P sprayed at anthesis has been seen to promote the active grain filling period and prolong senescence (Lv et al., 2017), but under adequate soil P and rainfall conditions foliar P application had no effect on grain P concentration (Wang et al., 2015). In a glasshouse experiment, Pierce et al., (2014) measured efficiency and recovery of H_3PO_4 applied to wheat foliage to be from 25 – 70% and 30 – 88% respectively. The proportion of plant P derived from foliar fertilizer accounted for 3 – 7% of the total plant P content in this study, which was significantly lower than P derived from soil and seed. Less translocation of P was also observed as rate increased. Foliar P had no effect on total plant P uptake but plants treated at mid-anthesis were more mature than those receiving P application at an earlier stage (Pierce et al., 2014). Mosali et al. (2006) in the United States explored an alternative to applying all of the P at time of seeding by only applying a portion of the total P requirement at seeding as granular MAP (11-52-0) in winter wheat, supplemented with a smaller amount applied as a foliar P spray later in the season. They indicated this may be more effective than applying all of the P recommended to the soil prior to seeding. Optimal time of application of foliar P is reported to be affected by physiological age, degree of P deficiency, and leaf area (Noack et al., 2012) and in wheat is suggested to be made some time between stem elongation (Zadocks 31) and before heading (Zadocks 47) (Noack et al., 2011). Application should occur when the plant is not under moisture stress (drought/ flood) (Denelan, 1988), and instead when crop is under P stress during active plant growth, likely during the transition from vegetative to reproductive growth when demand is high (Al Harbi et al., 2013; Silberbush, 2002). Foliar P application has been stated to be effective in high-fixing soils in which P applied to plant leaves is not subject to tie-up otherwise seen with soil P applications (Al Harbi, et al., 2013).

There is a lack of recent studies on crop response to foliar P fertilization, particularly in Western Canada. A growth chamber study conducted in 2004 with a Saskatchewan soil showed that foliar application of P on canola was not as efficient as soil applied P in meeting the total P requirement of the plant (Propp, 2004). In Manitoba, Green and Racz (1993) reported a yield benefit of 5 bushels per acre as the result of foliar P application on winter wheat. However, application of large amounts of foliar P is likely limited by the capacity of the leaves to sorb the P as well as risk of foliar burn. The greatest benefits have been observed under low moisture and highly P deficient soil conditions. Previous research suggests that a reduced rate of soil applied P at seeding supplemented with a foliar P application later could increase crop yield and quality. However there have been few studies on crops other than cereals, and little or no recent field-based information on foliar P efficacy for any crop on the Canadian prairies. McBeath et al., (2011) in a glasshouse experiment in Australia, evaluated foliar phosphate application on wheat on an alkaline calcarosol (pH 8.3, $CaCO_3$ content 14 % w/w) and an acidic ferrosol (pH 6.2) soil; both testing marginal for available P. Applying foliar $H_3PO_{4\,(aq)}$ with and without adjuvant resulted in no significant response to adjuvant treatment. Soil type was observed to influence P translocation efficiency. The acidic soil exhibited an increase in grain yield and grain P. The increase in grain P uptake was attributed to the increase in yield and not an increase in grain P concentration. The wheat in the calcarosol displayed little response to foliar treatments with an increase in stem P uptake but no increase in seed P uptake. However, the wheat in the calcareous soil exhibited significantly higher grain P concentrations. In the acidic soil, 83.2 % of plant P uptake was in grain while only 32.3 % of uptake was in grain in the calcareous soil. Total P recovery was less than 100 % in all cases which could be attributed to loss of foliar P through senescence of leaf tissue or translocation to the roots (McBeath et al., 2011). Another project evaluated foliar application of “Boost-52” (0:52:34) on soybeans in a low N and C, medium P, high K, slightly alkaline clay soil in India in which P application at both 35 days (d.) and 50 d. after seeding produced a significantly higher yield than no added fertilizer. The individual treatments at 35 d. and 50 d. were found to be equivalent. Foliar P application had no effect on oil content but the dual treatment significantly increased protein content; as did the individual treatments to a lesser extent (Garud et al., 2015).

The efficacy of foliar P fertilization (retention or repulsion) is dependent on the interactions between the fertilizer droplets and plant surfaces, and the same fertilizer formulation may perform differently depending on plant species, variety or organ applied to (Fernandez and Brown, 2013). Foliar P fertilizer that reaches the soil surface is likely to be immobilized due to strong soil sorption and be unavailable for plant uptake (Pierce et al., 2014). Greater contact area between fertilizer droplets and plant surface increases the chance of foliar uptake to occur through the cuticle or stomata (Fernandez and Brown, 2013). Low relative humidity (RH) and high temperatures observed in most arid and semi-arid regions are likely to reduce the rate of foliar uptake due to low cuticle hydration and drying of foliar solution (Fernandez and Eichert, 2009). Once the solution has dried out, the applied compound is essentially immobilized (Allen, 1970). Conversely there is a risk of the compound being washed off the plant but previous research has reported less than 10 % of applied foliar P as H_3PO_4 washed off for equivalent rates (Pierce et al., 2014). Furthermore, foliar treated plant tissue samples may contain both adsorbed and non-absorbed P remaining on the leaf surface which may obscure assessment of actual P uptake by the plant, and washing plant samples in an attempt to quantify adsorbed P may risk removing water soluble P (McBeath et al., 2011). It is important to consider the contribution of surfactants to foliar P uptake in which different surfactants affect wettability to varying degrees, making adjuvant selection important for wheat and other crops (Fernandez et al., 2014, Pierce et al., 2014).

2.3 Plant Phosphorus Speciation and Phytate

Phosphorus (P) is an essential macro nutrient, comprising about 0.2% of the plant dry weight (Schachtman 1998). In a plant, P is highly mobile and is distributed in different concentrations among the root, leaf, stem, and pod tissue. Phosphorus (P) in these plant parts may be returned to the soil upon plant death as soluble inorganic P, easily-degradable organic P or slower degrading organic P, all which contribute to recycling P back to the soil P pool (Noack et al. 2012). Phosphorus (P) is an important component of nucleic acids, phospholipids and ATP, and plants are unable to grow without a constant source of available P. Similar to plants, P is also an essential element to the human/animal diet as it is needed for energy metabolism, translating genetic information, maintaining cell structure and regulating Ca.

When adding P fertilizer and increasing fertilizer rates, it is important to consider possible adverse effects on seed nutritional content. An experiment done in South Australia by Noack et al. (2012) analysed the P speciation, bioavailability and distribution in the plant parts of wheat (*Triticum aestivum*), canola (*Brassica napus*) and peas (*Pisum sativum*). They found that phytate was the most prevalent form of P in the seed; accounting for more than 90 % of total seed P. Phytate (phytic acid) is located in the aleurone layer in most grains, making it more concentrated in the bran and is the major storage form of P in cereal and legume seeds (Coelho et al. 2002). Phytate however is considered an anti-nutrient for its ability to adsorb important minerals such as Zn, Fe and Ca in the gut of an animal, rendering those nutrients unavailable to the consumer (Singh et al. 2016). In cereal grain tissue, Fe and Zn have different speciation. Phytic acid (PA) is the main binding ligand of Fe while Zn is mainly bound to peptides (D. Persson, 2009). In 2005, using *Catharanthus roseus* cells, Mitsuhashi et al. found a direct correlation between high cellular orthophosphate concentrations and increased phytate production. Orthophosphate is a soluble inorganic, readily available P form. This suggests that P fertilization could affect the nutritional value of grains by affecting not only P content but also the content and bioavailability of other important nutrients like Zn and Fe. For example, the phytate: Zn molar ratio in grain is often used as an indicator of the bioavailability to humans of Zn in the grain, with a high ratio indicating lower bioavailability of the Zn contained within the seed.

An antagonistic relationship between soil P and Zn uptake has been well documented (Barben et al., 2010; Lu et al., 2011; Zhang et al., 2012) in which high soil P levels have been seen to reduce wheat grain Zn content and increase PA (Ryan et al., 2008). Foliar application may result in different levels and forms of P in the grain that will affect content and bioavailability of important nutritional micronutrients. However, some research suggests otherwise as Djalovic et al., (2008) found that high P rates only marginally increased seed and straw P compared to high nitrogen treatments. The source of P was also found to have little or no impact on grain nutritional status. Wang et al., (2015) combined liquid Zn with N and P as a foliar application in winter wheat and found that adding P reduced Zn absorption in vegetative tissue but did not affect Zn translocation to the grain. The added P significantly increased Fe and Ca concentrations in the grain and all treatments reduced grain PA content. Hatzack et al., (2000) evaluated phytate levels in low phytate A- and B-type barley mutants and found mutant seeds contained a fraction of the phytate that existed in parent material while phytate levels in the stem and root remained unchanged; the reduced phytate synthesis did not affect the mineral storage capacity of K, Mg, Ca and Zn in the seed. Selles et al., (2003) examined the effects of MAP and TSP on cadmium (Cd) uptake in two durum wheat (*Tricicum turgidum L. var. durum*) cultivars: Arcola (a low Cd accumulator) and Kyle (a high Cd accumulator). The most significant factors regarding uptake were genotype and environment while the source and placement or P accounted for only about 3% of Cd variability.

2.4 Soil Phosphorus Speciation and Runoff

Phosphorus (P) is immobile in the soil and therefore is not readily leached long distances vertically from the root zone. Instead the potential for P loss is mainly related to horizontal movement off-site in water runoff and erosion, which is of most concern in soils near rivers, lakes, or other water bodies. The annual precipitation in Saskatchewan ranges from 300-400 mm, one third of which occurs as snowfall while most summer rainfall is lost to evapotranspiration (Cade-Menun et al., 2013; Gray and Landine 1988). Snowmelt runoff contributes over 80 % of annual runoff and over 80 % of annual discharge into Saskatchewan rivers between April and June (Shrestha et al., 2011). Frozen soil inhibits infiltration and increases the distance of horizontal water flow, making it more likely to transport dissolved P ions to waterbodies (Cade-Menun et al., 2013; Young and Mutchler, 1976;). Much of Saskatchewan is dominated by agricultural land and the nutrient loss from this land due to water runoff is a significant cause of non-point source pollution (Carpenter et al., 1998; Correll 1998; Glozier et al., 2006). Nutrients are transported from soil to water as dissolved P in water runoff or as a particulate bound to suspended sediments (Correll 1998; Panuska et al., 2008). In loam textured Oxbow Orthic Black Chernozem in SE Saskatchewan, Cade-Menun et al. (2013) found cropland to have higher concentrations of dissolved P than particulate P in runoff. The influx of nutrients into waterbodies such as lakes or rivers is called eutrophication, which promotes symptoms such as cyanobacteria growth in fresh water systems (Kotak et al., 1993). This is problematic as the algal blooms create an anoxic zone causing death to marine flora and fauna, and creating foul smelling, non-palatable water (Kotak et al., 1994). Phosphorus (P) directly is non-toxic, however P imports are often the cause of eutrophication in lakes (Schindler, 1977), and water containing high P additions can be hazardous to human and animal health (Amdur et al., 1991). Agriculture is a major supplier of non-point source pollutant P.

There are numerous schools of thought about managing P runoff. Turner et al., (2003) found zero till practices reduced particulate P lost to erosion. Usage of conservation tillage and physical barriers to prevent soil particles from entering waterbodies have also been used to reduce nutrient loss from erosion and runoff (Kleinman et al., 2009; Usui-Kamppa et al., 2012). However, conservation tillage may enable accumulation or stratification of nutrients applied as chemical fertilizer(s) at the soil surface increasing the concentration of dissolved soluble reactive P ions in runoff (Ginting et al., 1998; Hansen et al., 2000; Li et al., 2011; Thiessen et al., 2010). Phosphorus (P) accumulation in the soil via fertilizer application may be beneficial agronomically and is not an environmental threat until the soils' capacity to retain P ions has been exceeded (Ige et al., 2005). Foliar P application may affect the content of soluble mobile P at the soil surface compared to in-soil placement, thereby affecting potential export in run-off. However, the impact of foliar versus soil applied P fertilizer on P export in snowmelt run-off on the prairies is unknown.

3.0 AGRONOMIC CROP RESPONSE TO FOLIAR PHOSPHORUS FERTILIZATION

3.1 Preface

This chapter evaluates the yield and P uptake response of pea, wheat and canola under controlled environment and field conditions, to varying proportions of seed-placed MAP and foliar applied KH_2PO_4 fertilizer. This chapter also consider the nutritional impact of foliar P fertilizer application on seed Zn, Fe and phytate levels, and residual P in the soil after harvest.

3.2 Abstract

In 2016 and 2017, canola, pea and wheat were grown at four field sites in the agricultural region of Saskatchewan, providing contrast in soil and environmental conditions. The study was set up as RCBD field experiments conducted near Pilger (Krydor soil association), Central Butte (Echo association), Rosetown (Sutherland association), and Mawer (Weyburn association) SK, along with CRD controlled environment experiments that were conducted in the winter of 2016 using soil taken from the control plots from the 2016 Pilger and Central Butte sites. Each crop received a P treatment of 20 kg P_2O_5 ha^{-1} with varying proportions of seed placed MAP and foliar KH_2PO_4 applied mid-season after canopy closure prior to anthesis. All crops received a blanket application of urea (46-0-0) at 100 kg N ha^{-1} and 44 kg K_2O ha^{-1} + 17 kg S ha^{-1} as potassium sulphate (0-0-44-17), except pea received no N fertilizer. Canola was generally the most responsive to foliar P treatment though results varied with site. Generally, yield response decreased as the proportion of seed placed MAP decreased and proportion of foliar P increased. The 20 kg P_2O_5 ha^{-1} applied entirely as foliar in canola was observed to maintain significantly higher yield than the unfertilized control in the absence of seed-placed MAP, indicating some uptake and response potential from foliar applied P. In soils with the lowest P fertility according to soil test, the yield and P uptake showed greatest response to seed-placed MAP versus foliar P fertilizer. Foliar P applied mid-season appeared most effective as a top-up rather than a replacement for seed-row applied P. Its value may be greatest when there is risk of injury from seed-row placed fertilizer such as with canola and pea, as was observed at two of the sites in dry years. Of the crops evaluated, canola was most responsive to P fertilization, followed by wheat, while pea showed no significant ($P<0.10$) responses in either the field or controlled environment. Response was most profound at the Pilger site but was not consistent over two growing seasons while little response was observed at the Central Butte and Rosetown sites. It is important to consider nutritional aspects such as Zn, Fe and phytate content in grain as affected by fertilization as they are important for human health and phytate is an anti-nutrient that renders micronutrients such as Zn unavailable for digestion. In this study phytate content ranged from 68 to over 90% of total seed P, with the highest proportions in wheat grain. Fertilizer treatment had little effect on grain Fe content however, there appeared to be an inverse relationship between seed-placed MAP and grain Zn concentration that was less evident with P applied in foliar form. Under the conditions evaluated in this study, foliar P application was unable to substitute for seed placed MAP, and overall had marginal effect on grain yield and P uptake, residual soil available P, as well as seed nutritional value.

3.3 Introduction

Foliar fertilization has been promoted as a more effective and environmentally friendly application strategy than soil placed fertilizer, as nutrients can be directly applied to plant tissue during peak demand, by-passing potential fixation and losses from soil. However, the efficacy of foliar fertilizer is uncertain (Fernandez et al., 2013). For annual crops, small amounts of P fertilizer are often placed near the seed at time of sowing as a starter to enable early access, but amounts are limited due to injury from the salt effect of the fertilizer. Furthermore, soil placed P is susceptible to reductions in solubility and availability due to adsorption and precipitation reactions with soil minerals, especially in calcareous soils (Bertrand et al., 2006). Because of these limitations, applying a proportion of P fertilizer as a foliar spray may help address P deficiency by providing a top up during the growing season. Foliar P has been recommended when plant P demand is high and soil conditions limit the uptake of soil applied fertilizer or losses of the applied fertilizer are high (Fernandez et al., 2013). A more detailed coverage of the forms and fate of fertilizer P in soils and plants in provided in the literature review of this thesis (see Chapter 2).

The reported efficacy of foliar P fertilizers in addressing plant P deficiencies and eliciting a crop response covers a spectrum of generally neutral to positive observations (e.g. Green and Racz, 1999; Mosali et al., 2006; Noack et al., 2011). Factors believed to affect response to foliar P include crop type, crop stage, climate, soil and foliar solution pH, application strategy (droplet, mist, and surfactant) and timing (Fernandez et al., 2013). Concerns surrounding foliar P fertilization have included potential antagonistic effects on Zn uptake and bioavailability (Zhang et al., 2012). Fertilizer P has been associated with increased phytate production in grain which can bind to Zn, rendering it unavailable for human digestion (Singh et al. 2016) and it is not well established as to whether foliar P application significantly affects nutritional parameters of grain. High concentrations of orthophosphate in plants have been associated with increased plant phytate (Mitsuhashi et al., 2005). Overall uptake potential of foliar P is generally considered to be relatively low, but increased P use efficiency has been reported with foliar P (Noack et al., 2011). However, foliar application as a P fertilization strategy and its impacts on crops and soils has received relatively little attention in cropping systems of the Canadian prairies.

The goal of the research described in this chapter was to determine the crop and soil responses to foliar P applied alone, and in combination with soil applied P fertilizer. This was addressed by determining the effect of different proportions of soil and foliar P applied to different crops (canola, wheat, and pea) on yield, nutrient uptake and grain composition (Zn, Fe, and phytate) and residual available P in the soil. To provide contrast in soil and environmental conditions, farm fields in the Brown, Dark Brown and Black soil climatic zones were selected and used to provide soil for controlled environment studies and site locations for field trials conducted in 2016 and 2017. The objectives for this chapter have been previously outlined in chapter 1.0.

3.4 Materials and Methods

3.4.1 Site selection

This component of the research involved two field seasons: 2016 and 2017, and growth chamber and field experimental work. The project utilized three different crops: Argentine canola (*Brassica napus* var Invigor LL252 in 2016; VT 500 RR in 2017), hard red spring wheat (*Triticum aestivum* var Waskada both years), and green pea (*Pisum sativum* var CDC Sage both years) that were seeded in soils believed to be deficient to marginally deficient in P according to soil test and therefore potentially responsive to P fertilization. The chosen sites were selected on the basis of being farm fields that were typical representations of the soil-climatic zone and management practices currently used by growers. The three sites used in 2016 were: 1) near Pilger SK, a Black Chernozem loam soil located at 31-39-24-W2; 2) near Rosetown SK, a Dark Brown Chernozem loam soil located at 6-30-14-W3, and 3) near Central Butte, SK, a Brown Chernozem/Solodized Solonetz soil located at SW33-21-4-W3. A fourth site in 2016, located near St. Brieux, SK, was lost to flooding in July and data that could be salvaged is reported in the appendix. The 2017 season utilized three sites: 1) near Pilger, SK, a Black Chernozem adjacent to the field used in 2016; 2) near Mawer, SK, a Dark Brown Chernozem located at 36-20-3-W3 and 3) near Central Butte SK, in a Brown Chernozem/Solodized Solonetz soil adjacent to the field used in the 2016 field season.

The sites at Central Butte and Rosetown were located in upper slope positions of landscapes that were calcareous and had experienced some past erosion, while the Pilger and Mawer sites were located on fields that were relatively level. Qualitatively, the ranking of soil P deficiency according to the Modified Kelowna extractable P level (ALS Labs, Saskatoon) was marginally deficient for the Central Butte, Rosetown and Mawer sites, deficient to marginally deficient for Pilger site, and was marginally deficient to sufficient for St. Brieux site. Based on extractable P levels, P fertilizer recommendations were made by ALS™ laboratory (Saskatoon, SK) for all crops at all sites. This resulted in selection of 20 kg P_2O_5 ha^{-1} as the total amount of fertilizer P applied (seed-row plus foliar) for the treatments for the three crops at all sites in 2016 and 2017. The rate of 20 kg P_2O_5 ha^{-1} is a safe rate of fertilizer to be applied in the seed row for all crops used in the study (Saskatchewan Ministry of Agriculture Guidelines for Maximum Safe Rates of Seed-Row Placed Fertilizer). The 2017 sites at Central Butte and Pilger were fields within 1 km of where the 2016 sites were located.

3.4.2 Field small plot study design and treatments

The field experimental design was a randomized complete block design with separate blocks for each crop: canola, wheat and pea. For each crop, five randomized fertilizer treatments in four replicate blocks were used. The treatments were: 1) control with no added P; 2) 20 kg P_2O_5 ha^{-1} seed placed as mono-ammonium phosphate (MAP 11-52-0); 3) 15 kg P_2O_5 ha^{-1} seed placed as MAP and 5 kg P_2O_5 ha^{-1} foliar applied; 4) 10 kg P_2O_5 ha^{-1} as seed placed MAP and 10 kg P_2O_5 ha^{-1} as foliar applied P; 5) no seed placed MAP with all 20 kg P_2O_5 ha^{-1} as foliar applied P. The rate of 20 kg P_2O_5 ha^{-1} was selected as it is the maximum amount of P fertilizer that can safely be applied to canola, wheat and pea. The foliar P source used was monopotassium phosphate (KH_2PO_4) dissolved in water and with an activator adjuvant added as recommended to promote foliar absorption (Table 3. 1). Monopotassium phosphate (KH_2PO_4) was used because KH_2PO_4 fertilizer is soluble and has been used in previous studies of foliar P nutrition (e.g. Green and Racz, 1999). Any potential effect of K in the foliar treatment was assumed to be negated by high available K content of soils at the sites, with soils deemed not deficient in K according to soil test. Further, a blanket application of K fertilizer was made to override possible influence of the treatments on K nutrition and yield. Each wheat and canola plot received a blanket application of urea (46-0-0) at 100 kg N ha^{-1} equivalent and 44 kg K_2O ha^{-1} + 17 kg S ha^{-1} as potassium sulphate (0-0-44-17). Nitrogen was not added to the pea plots and the peas were inoculated with *R. leguminosarum* commercial inoculant. Each plot also received a blanket application of Zn and copper sulphate at 5 kg Cu ha^{-1} and 5 kg Zn ha^{-1}. Application of foliar P fertilizer was made in-season for each crop at a time corresponding to when another crop protection operation (fungicide or insecticide) was conducted to increase the practicality of foliar fertilization for the grower. Foliar P fertilizer was applied using a fan nozzle on a hand sprayer to minimize fertilizer drift. The foliar P was applied to each crop during canopy closure, as this is typically a time of high disease pressure and when there is ample opportunity for leaf interception of foliar applied P. In the pea this was the 6-9 node stage, in canola the 5-8 leaf stage before bolting, and near flag leaf emergence (Zadoks 32 - 37) for the wheat.

Table 3.1 Description of liquid foliar P treatments.

Rate	Water Volume		Concentration
kg P_2O_5 ha^{-1}	L ac^{-1}	mL plot^{-1}	g L^{-1}
5	43.5	13.1	115
10	43.5	13.1	230
20	87.0	26.1	230

Phosphorus source is K_2PO_4. Commercial adjuvant "Xiameter" is added at 0.125 % volume. Plot area is 0.0003 ac.

Seeding rates of pea, wheat and canola were 140, 100, and 6 kg ha^{-1} respectively with Central Butte and Mawer sites seeded in first week of May, Rosetown in the second week and Pilger in the third week of May in both 2016 and 2017. Plots were 3 m^2 with three rows in each plot of 3 m length, 25cm apart and the plots 50 cm apart. Harvest of above-ground crop grain and straw biomass was conducted in the last two weeks of August using hand sickles. The harvested area consisted of two one meter row lengths (1 m^2) as representative plot samples to account for variability during seeding taken from each plot. Harvested plant samples were placed in cloth bags and air-dried at 30^{o}C before analyses.

Figure 3.1 Foliar P study Mawer field site July 5, 2017.

3.4.3 Plant and soil analyses

Pre-seeding samples of soil were taken from each site in a linear transect diagonally across the plot area, Soil samples were bagged and immediately frozen at -20 ^{o}C until further processing. Samples were then thawed and allowed to air-dry at 30 ^{o}C for one week and then ground using a flail grinder to pass through a 2-mm sieve and collected in a 40 dram vial. Dried and ground samples were stored at room temperature until laboratory analysis. Samples were used to measure extractable nitrate, sulphate, pH and EC, at 0-15, 15-30 and 30-60cm depths, as well as soil organic C, and soil test P in the 0-15cm depth. Post-harvest soil samples were taken from each plot at the aforementioned depths and measured for extractable nitrate, sulphate, pH, EC and organic C to assess residual nutrient availability. Measurements made on harvested crop samples were crop grain and straw yield, P concentration and above-ground uptake at harvest, grain phytate (Wade's Reagent) and Zn and Fe (hot sulfuric acid digest) content in grain to assess any potential effects of the treatments on micronutrient availability. Above-ground plant samples were also taken midseason, both before and after the foliar P application, to assess the effect of the added foliar P on plant P concentration. Detailed description of the methods used follows below.

After harvest, soil labile P was measured in the surface soil using a water extraction method developed and described by Schoenau and Huang (1991). A 1:50 soil:water solution was prepared by adding 100 mL of distilled water to 2.0 g of soil in a 100 mL plastic container. The containers are shaken for 1 hr at 200 rpm, then the suspension was passed through a 0.45 µm Millipore™ filter. Samples were stored at 4 ^{o}C, then analyzed colorimetrically for orthophosphate according to the Murphy and Riley method (1962) to determine the levels of labile, water extractable inorganic P in each soil sample.

To measure potential root uptake of P, the supply rates of available soil P were measured using ion exchange membranes (Qian and Schoenau, 2002). Two vial caps were filled with soil and brought to field capacity with distilled water. A charged anion membrane was placed between the soils of both caps and sealed with parafilm for 24 hrs. After 24 hrs, the caps were pulled apart and the membrane removed and washed free of any adhering soil with distilled water. The membranes were then eluted with 0.5 *M* HCl and the eluent analysed for orthophosphate using the Technicon™ automated colorimeter.

Total N, P, Fe and Zn content of plant and soil material were measured using a hot acid digest performed on ground grain and straw outlined by Thomas et al. (1976). Briefly, ground, dry samples of 0.2490-0.2509 g were weighed, transferred into test tubes, then received 5 mL of concentrated (18*M*) sulfuric acid. The test tubes were placed on a heating block and heated for 30 min at 360 ^{o}C. Tubes were then cooled for 20 min and received 0.5 mL of 30 % w/w hydrogen peroxide (H_2O_2) and mixed by vortexing. Heating and cooling was repeated (with repeated H_2O_2 addition) until the solution in the tubes became clear. To remove all H_2O_2, samples received additional H_2O_2 and were then heated for 60 min. Samples were allowed to cool once more before being brought to volume (75 mL) with distilled water. Tubes were capped and inverted to mix the solution. The extract was analysed using atomic absorption/ flame emission spectroscopy (AA/FES) for K, microwave plasma emission spectroscopy for S, and N using the Technicon™ automated colorimeter.

Soil extractable, available P and K were measured by modified Kelowna extraction. Kelowna solution was prepared by dissolving the constituents into distilled water producing a solution with 1.4 % (w/w) acetic acid, 1.9 % (w/w) ammonium acetate, and 0.056 % (w/w) ammonium fluoride. A bottle containing 30 mL of Kelowna solution received 3 g of air dried soil and was placed on a rotary shaker for 5 min at 142 rpm. The mixed solution was filtered through VWR 454 filter paper and refrigerated at 4 ^{o}C until analysed for phosphate using the Technicon™ automated colorimeter and K analysed using flame emission spectroscopy on an Agilent™ AA-Fe spectrometer.

Extractable soil nitrate and sulphate was determined using calcium chloride ($CaCl_2$) extractant prepared by dissolving 1.11 g of $CaCl_2$ in 1.0 L of distilled water. In the extraction 20 g of soil was combined with 40 mL of the $CaCl_2$ solution in an extraction bottle and placed on a rotary shaker at 142 rpm for 30 min. The soil suspension was then filtered through Whatman #42 filter paper into 7 dram vials. The vials are stored at 4 ^{o}C until analysed for ammonium and nitrate by the Technicon™ colorimeter.

Soil extractable Zn and Fe were determined by DTPA extraction using the methods described by Lindsay and Norvell (1978). In 200 mL of deionized water, 149 g of 0.1 M triethanolamine (TEA), 19.7 g of 0.005 M Diethylenetriaminepentaacetic acid (DTPA), and 15 g of 0.01 M $CaCl_2$ were added to the water until DTPA was fully dissolved. Using 1 M HCl, solution pH was brought to 7.3, and solution was brought to 10 L volume with deionized water. Thirty grams of air dried soil was mixed with 60 mL of DTPA solution and shaken for 2 hrs on rotary shaker at 142 rpm. Extract was filtered through Whatman #42 filter paper and analysed on the auto analyser. The Fe and Zn concentrations in the extract were measured using an Agilent™ atomic absorption spectrometer.

Soil electrical conductivity and pH was measured with a 2:1 water to soil solution placed on a rotary shaker at 1425 rpm for 20 min. The bottles are left to settle for 1 hr, after which the solution was filtered through Whatman #1 filter paper into 7 dram vials to be measured with a pH and EC probe.

Seed phytate content of wheat and pea samples was measured in the University of Saskatchewan Crop Development Centre Pulse Lab using the method outlined by Vaintraub and Lapteva (1988) and modified by Gao et al (2007). This method is based on use of "Wade's Reagent". Ground seed samples of 0.05 g were placed in micro tubes which received 1 mL of 0.8 M HCl and shaken for 24 hrs. Samples were then centrifuged at 8000 rpm for 20 min before transferring 10 µL of extract into a fresh micro tube. The extract received 740 mL of distilled water and 250 mL of modified Wade's reagent. From each duplicate 200 µL was transferred into a microplate cell and read in an autoanalyzer at 490 nm. The standards used were prepared with PA dodecasodium salt hydrate at concentrations of 50, 100, 200, 300, 400 µL PA dodecasodium salt hydrate per mL.

3.4.4 Growth chamber controlled environment studies

The growth chamber study component of the research was conducted during the winter months of 2016 and 2017 in the University of Saskatchewan College of Agriculture and Bioresources phytotron facility. The study was performed using surface (0-15 cm depth) soil collected from the control (no P fertilizer added) wheat plots at each field site. It was used to evaluate crop and soil response (this chapter), and determine P export in run-off (Chapter 4) as affected by P fertilization treatment under controlled conditions. The growth chamber study used hard red spring wheat (var Waskada), green pea (var Sage), and Argentine canola (Invigor L252). Two different soils were used for each crop: the Central Butte SK site Echo association soil and the Pilger SK site Krydor association soil. For logistical purposes plastic potting trays were used in which each tray is separated into two equal compartments using a plastic divider that seals each compartment, and each compartment was also lined with 6 mm poly-plastic to separate the compartments. A quantity of 3 kg of soil was used in each compartment which were watered to 80 % field capacity to prevent periods of standing water.

The experiments using the trays of soil in the controlled environment chambers were set up as a completely randomized design in which each compartment was randomly designated a fertilizer treatment. Tray position and orientation in the chamber was altered every four d. to account for any uneven growing conditions in the chamber. Sources of fertilizer N, P, K, and S were as in the field studies: urea (46-0-0), MAP (11-52-0), and potassium sulfate (0-0-44-17). Monopotassium phosphate (K_2PO_4) dissolved in water was used as the foliar P fertilizer applied at canopy closure, as described for the field component. There were four replicates of 3 P treatments and a control treatment as follows: 1) control (0 P added), 2) seed placed P at 20 kg P_2O_5 ha^{-1}, 3) seed placed P at 10 kg P_2O_5 ha^{-1} + foliar applied P at 10 kg P_2O_5 ha^{-1}, 4) foliar applied P at 20 kg P_2O_5 ha^{-1}. Pea, wheat and canola were seeded in each compartment at rates of 140, 100, and 6 kg ha^{-1} respectively, and thinned to 3 healthy plants per compartment. Foliar P treatment was applied at canopy closure. Pea received treatment at the 8-12 node stage, wheat at flag leaf and canola at rosette stage. For the vegetative growth stage, crops were grown under 18 hr light and 24 ^{0}C then switching to 14 hr light. Crops were harvested after seeding, prior to full maturity and plant samples were oven dried at 40 ^{0}C prior to analyses. Soil and plant analytical methods used on soil, plant and water samples from the controlled environment studies were the same as described for the field studies previously in section 3.3.3.

Figure 3.2: Foliar P controlled environment study in University of Saskatchewan phytotron.

At the beginning of the growth chamber study, soil samples were analyzed for extractable N, P, K and S, pH and EC. Anion exchange membrane probes were used to assess the soluble, exchangeable P concentrations at the surface to determine potentially mobile P at the surface that could interact with snowmelt runoff. Probes were placed at the soil surface 3 d. following seeding, as well as before and after foliar P application, and at the end of the experiment. Two probes were placed approximately 5 mm beneath the soil surface of each compartment: one along the fertilizer band, and one crossing the seed row. Probes were cleaned and eluted in 0.5 M HCl and the solution was analyzed colorimetrically using an autoanalyzer as described in section 3.3. Dried plant samples were analyzed for total element concentration by hot acid digestion outlined by Thomas et al. (1976) and described previously.

To assess how foliar treatments influence P export off-site in snowmelt runoff water under controlled conditions, a simulated snowmelt study was conducted on each replicate after plant harvest. This is not covered here but is described in detail in Chapter 4 that follows.

3.4.5 Statistical data analysis

Statistical analysis was done using PROC GLIMMIX in SAS (version 9.4; SAS Institute, Cary, NC). Where applicable, means separations were performed using Tukey's protected HSD. Tukey's protected HSD was used for multi-treatment comparisons. Treatment and crop were analysed as fixed treatments with block analysed as a random effect. Outliers were determined by Grubbs Test. An alpha level of significance of 0.05 was chosen to deem a treatment effect as significant in the controlled environment experiments, while a level of 0.10 was used in the field studies. The higher alpha level in the field component was chosen to reflect the generally higher degree of variability encountered with small plot size and hand-application and harvesting of the crop samples in the field. P values are reported in ANOVA tables for main treatment effects and interactions.

3.5 Results and Discussion

3.5.1 Site soil characterization

The basic soil properties including pH, electrical conductivity (EC), organic carbon (OC) and extractable available P using modified Kelowna extraction (MK-extractable P) for the research sites are shown in Table 3.2. The spring MK-P assessment indicates the Pilger sites to be the most soil P deficient in 2016 and 2017. Low intial extractable available P according to soil test should provide conditions which promote response to P treatment as long as crop demand for P is high (Al Harbi et al., 2013). This would be the case under the 2016 growing conditions in southern SK, but dry conditions in 2017 particularly at the Central Butte and Mawer sites would limit the crop demand. The highest organic carbon (~4.5%) was found in the Pilger sites over both years, consistent with the higher soil organic matter (SOM) content associated with Black soils. The lowest OM (1.1%) was measured at the Central Butte site located in the Brown soil zone. The pH values of all sites were neutral to basic ranging from 7.9-8.3. The Pilger location has the highest pH values which is consistent with the more calcareous nature of the soil in that region, with carbonates evident by effervesence throughout much of the profile. The innately high P fixing behavior of calcareous soil at the Pilger location should promote foliar P efficacy (Al Harbi et al., 2013). The EC values were low and similar across all sites, indicating non-saline conditions. The site at Central Butte in 2016 had slightly higher EC than the other sites, consistent with wet conditions that spring, and the poorly drained and saline-solonetzic nature of the Echo association soils with their Bnt horizon.

Table 3.2: Modified Kelowna extractable P, pH, EC and organic C (0-15 cm depth) at the three field sites in 2016 and 2017.

		MK-extractable P mg P kg^{-1}†		pH		EC mS cm^{-1}		OC %	
Site	Association	2016	2017	2016	2017	2016	2017	2016	2017
Pilger	Krydor	7	6	8.1	8.3	0.2	0.2	4.4	4.5
Central Butte	Echo	11	9	7.9	8	0.6	0.1	1.1	1.3
Rosetown	Sutherland	12	*NT*‡	7.9	*NS*	0.2	*NS*	1.7	*NT*
Mawer	Weyburn	*NT*	8	*NT*	8.1	*NT*	0.1	*NT*	1.3

† Modified Kelowna (MK)-extractable P was analyzed by ALS labs in Saskatoon SK.
‡ *NT* denotes no trial was conducted at that location that year.

3.5.2 Weather data

Temperature and precipitation data for the 2016 and 2017 seasons at the sites are shown in Table 3.3 and indicate two contrasting growing seasons in southern Saskatchewan in general: wet in 2016 and dry in 2017. The 2016 Pilger location weather data shows the area received below average rainfall in the spring and early summer but above average rainfall through the middle and towards the end of the season including a wet July with almost double the previous 5 year average of rainfall. Comparatively, in 2017 the Pilger site location had above average spring moisture but below average rainfall throughout the growing season and finished with less than the average seaosnal rainfall. Pilger temperatures were similar to the previous 5 year average for 2016 and 2017. In 2016, the Central Butte site received above average rainfall for most of the growing season and finsished with 63 mm more total precipitation than the previous 5 year average. However, the 2017 season was very dry at the Central Butte and Mawer sites in south-central SK, which had dry conditions in spring that persisted throughout the growing season and finished the season with 161 mm less total rainfall than the average for the previous five years. Temperatures were slightly cooler than average in 2016 and 2017 at the Central Butte and Mawer sites. The Rosetown site location, which was used in 2016 only, received about average spring precipitation but well above average summer rainfall and in total received 162 mm more rainfall than the previous 5 year average. However, the upper slope location of the Rosetown site allowed for adequate drainage throughout the growing season, preventing long standing periods of saturation or standing water that was detrimental to crop growth and yield in the surrounding Rosetown area.

Table 3.3: Average monthly air temperature and precipitation at the field trial sites in 2016 and 2017 and the previous 5 year average using data from the nearest Environment Canada station (Cudworth (Pilger), Rosetown) or meterological station (Central Butte, Mawer).

		2016		2017		Average 2011-2015	
Site	Month	Air Temperature ºC	Precipitation (mm)	Air Temperature ºC	Precipitation (mm)	Air Temperature ºC	Precipitation (mm)
Pilger	May	16	33	12	90	14	39
	June	19	76	17	75	18	112
	July	20	126	22	44	21	64
	August	19	54	20	44	20	50
	September	13	45	13	33	15	27
	Total		334		286		292
Central Butte/ Mawer	May	13	108	14	7	14	71
	June	18	70	17	31	19	77
	July	19	89	22	35	23	53
	August	17	53	19	45	23	46
	September	12	35	13	14	17	46
	Total		355		131		292
Rosetown	May	16	39	none†	none	13	54
	June	19	72	none	none	18	81
	July	20	141	none	none	22	44
	August	18	100	none	none	22	39
	September	13	46	none	none	16	18
	Total		398		none		236

The Central Butte and Mawer sites are grouped together as one meteorological station was located between the two sites located 18 km apart. No Rosetown site in 2017.
† Cells labelled as none indicate no data was taken for that site.

3.5.3 Yield and phosphorus uptake

3.5.3.1 *Controlled environment studies*

Pilger Site: Krydor Association

The total biomass yield of crops grown on the Pilger soil under controlled environment conditions showed a similar pattern in canola yield to the Central Butte Echo association soil, where the SP treatment had significantly higher yield than the other treatments, and was significantly greater than the C and F(100) treatments. Both F(50) and F(100) were significantly greater than the control treatment at the Pilger site. The overall large response of canola biomass yield to P fertilizer addition observed on the Pilger soil is in agreement with the low available P content (Table 3.3) of this soil. There was a trend for response in wheat, but no significant response to fertilizer treatment was observed in the Pilger wheat or pea crops. Generally, pulses are comparably better scavengers for soil P than many other crops (Hinsinger et al. 2003) and their ability to access this P can result in pulses being less responsive to P fertilization.

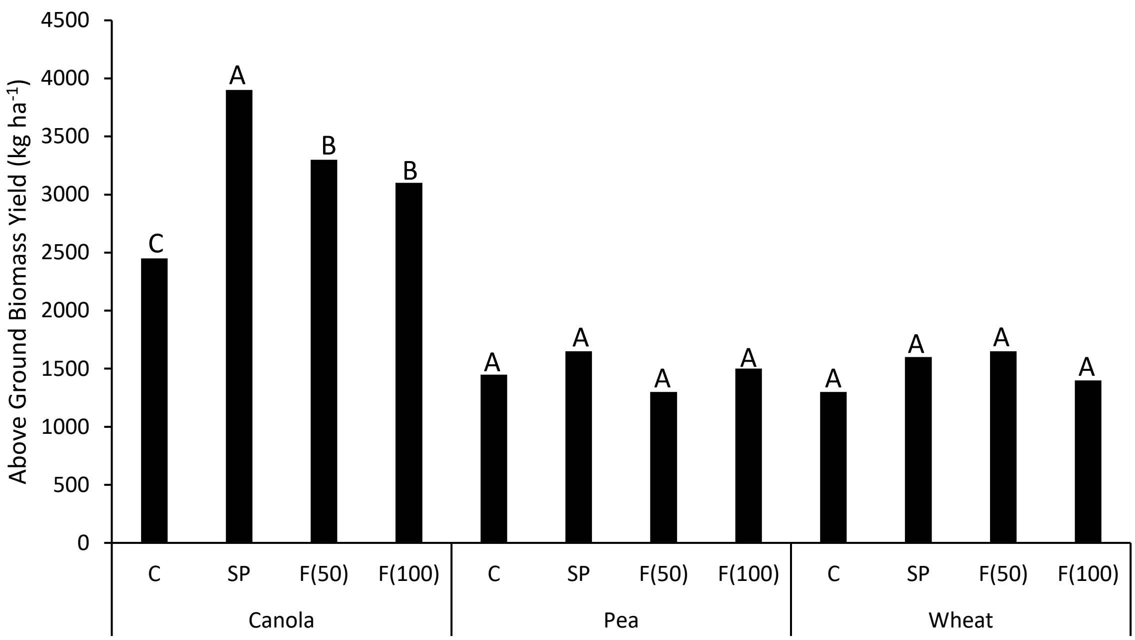

Figure 3.3: Above ground biomass yield in controlled environment trial with Krydor association soil from Pilger site. Means were separated using Tukey's protected HSD (α=0.05). Means with same letter within same crop are not significantly different. All P fertilized treatments received a total of 20 kg P_2O_5 ha^{-1}. Treatments labelled C, SP, F(50), F(100) denote control, all P seed-placed, 50% P seed placed and 50% applied as foliar, and 100% P applied as foliar P, respectively.

Central Butte Site: Echo Association

The controlled environment study conducted on the Echo association soil collected at the Central Butte location revealed that of the three crops evaluated, canola was the most responsive to foliar P application in total above-ground biomass (grain + straw), followed by wheat and pea (Fig 3.3). Similar findings were also observed in the field at this site (see section 3.4.3.2). In canola, the SP treatment produced significantly more total above-ground biomass than the C and F(100) treatments, while the F(50) treatment was only significantly greater than the control treatment. Overall, in the canola, total biomass production decreased as the proportion of seed placed P decreased, suggesting lower uptake efficiency associated with foliar P treatment than seed placed P. No significant differences were observed amongst any treatments in pea or wheat.

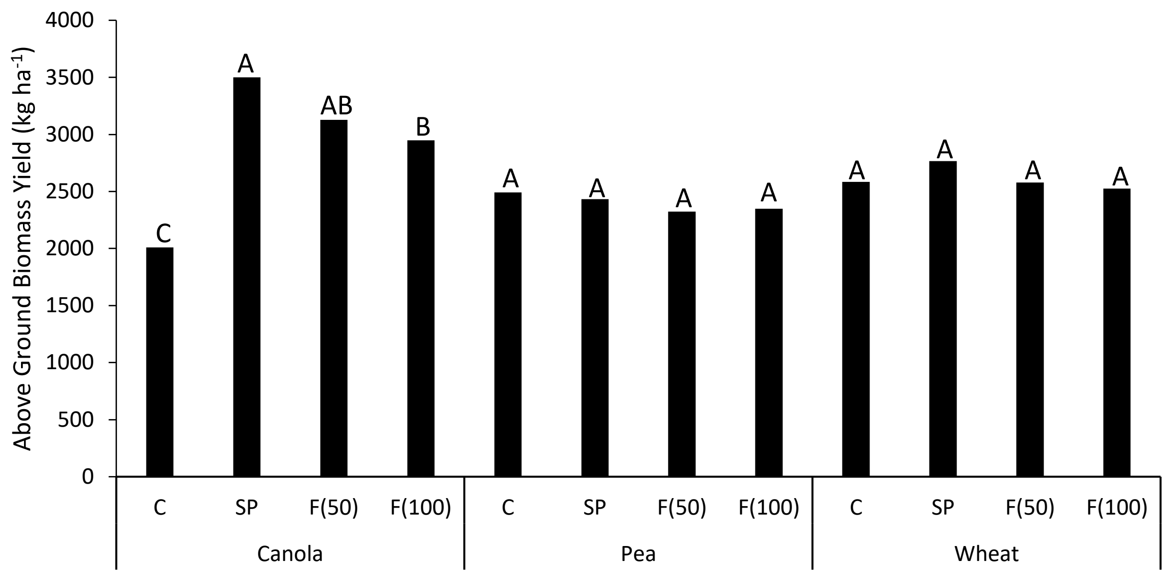

Figure 3.4: Above ground biomass yield in controlled environment trial with Echo association soil from Central Butte site. Means were separated using Tukey's protected HSD (α=0.05). Means with same letter within same crop are not significantly different. All P fertilized treatments received a total of 20 kg P_2O_5 ha^{-1}. Treatments labelled C, SP, F(50), F(100) denote control, all P seed-placed, 50% P seed placed and 50% applied as foliar, and 100% P applied as foliar P, respectively.

The grain yields from the controlled environment study on the Echo association soil from Central Butte (Fig. 3.5) reveal a slightly different trend than the total above ground biomass. Both SP and F(50) produced higher canola grain yield than the unfertilized control, and the yields among the fertilized treatments were not significantly different. These findings suggest that foliar P may be more beneficial for canola grain yield than straw and might be explained by more rapid redistribution of foliar P when pod filling is occurring. As was observed for total above ground biomass, no significant difference among treatments was found in the pea or wheat grain yields. Overall grain yields in the controlled environment study were relatively low, which can be attributed to the restricted rooting volume the crops experience in pots and lighting conditions of controlled environment chambers that cannot duplicate natural sunlight.

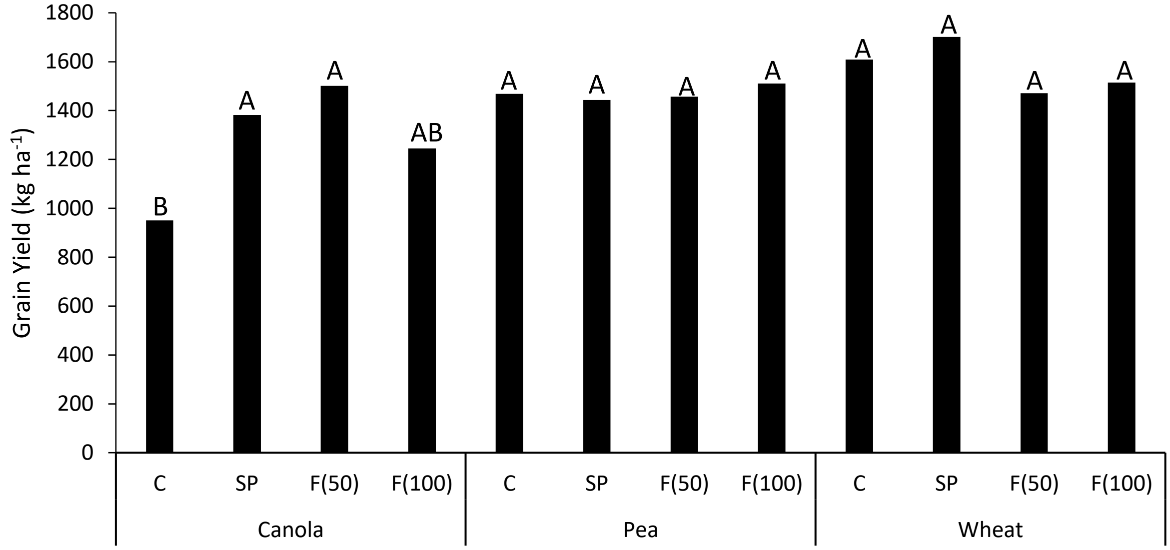

Figure 3.5: Grain yields in controlled environment trial with Echo association soil from Central Butte site. Means were separated using Tukey's protected HSD (α=0.05). Means with same letter within same crop are not significantly different. All P fertilized treatments received a total of 20 kg P_2O_5 ha^{-1}. Treatments labelled C, SP, F(50), F(100) denote control, all P seed-placed, 50% P seed placed and 50% applied as foliar, and 100% P applied as foliar P, respectively.

The addition of P fertilizer at 20 kg P_2O_5 ha^{-1} to canola grown on the Echo association soil from Central Butte increased P uptake in grain and straw in all fertilizer addition treatments (Table 3.4). There was no significant difference among seed placed, foliar and the combination treatments. For pea, there was no difference among any of the treatments, including the control, in P uptake in the grain and straw, and values were all similar. The lack of response of the pea in P uptake to P fertilization follows the lack of response of the pea in yield, and can be attributed to the ability of this crop to efficiently scavenge P already present in the soil. Lack of response of pea to P fertilization has been observed in other studies in western Canada such as Walley et al. (2005). In wheat, only grain P uptake responded to fertilization, and was highest when all the P was seed-placed followed by the F(50) treatment, pointing to greater effectiveness of the seed-placed P. Wheat straw P showed no significant response to foliar P application and neither pea grain nor straw uptake was significantly affected by P fertilization strategy. Overall, especially for pea and wheat, much of the above-ground P uptake was in the grain, which was removed at harvest.

Table 3.4: Grain and straw P uptake (kg P ha^{-1}) from crops grown in Echo association soil from the Central Butte site under controlled environment conditions.

Crop	Treatment†	Straw P	Grain P
		————kg P ha^{-1}————	
Canola	C	0.71c‡	1.13b
	SP	1.68a	2.11a
	F(50)	1.24a	2.41a
	F(100)	1.62a	2.04a
Pea	C	0.89§	2.23
	SP	0.98	2.53
	F(50)	0.76	2.34
	F(100)	0.78	2.33
Wheat	C	0.66	2.24c
	SP	0.67	3.25a
	F(50)	0.77	2.73b
	F(100)	0.80	2.48cb

† Treatments C, SP, F(50), F(100) denote control, seed-placed, 50% P applied as foliar, and 100% P applied as foliar respectively.
‡ Means were separated using Tukey's protected HSD (α=0.05). Means with same letter within same crop and column are not significantly different (α=0.05).
§ No letters indicates no significant difference (α=0.05).

Comparatively, canola was more responsive to foliar P treatment than wheat which may be due to leaf morphology and better overall interception of foliar fertilizer than wheat or pea. This also has implications for loss of P in runoff as covered later in Chapter 4 of this thesis. At time of foliar P application, the canola leaf canopy was visually observed to cover the entire surface area of the tray while wheat and pea did not. This likely resulted in more foliar P reaching the soil surface in the wheat and pea than the canola, reducing availability and uptake, and limiting overall response to foliar treatment. As P is relatively immobile, foliar P ending up on the soil surface is likely to be less root available (Pierce et al., 2014). However, it is important to note that in the chamber, the continual addition of water to the trays and the restricted root volume would likely improve the chances of the foliar P at the soil surface moving to, or being intercepted for root uptake compared to the field. One also must recognize that the foliar application occurred at the time of canopy closure, while seed placement provided all P available for uptake immediately following germination. The results of the current study suggest no benefit from a split application. Some research has suggested foliar P to have promising efficiency advantage compared to soil applied P (Barel and Black 1979; Marshall and Wardlaw 1973; Pierce et al., 2014). However much of this research has been conducted under controlled conditions using targeted droplet applications on wheat. Spray and mist applied foliar P that would be more commonly associated with field applications with a fan nozzle equipped sprayer is unlikely to produce similar efficiency. In this controlled environment study, the relatively narrow shape of wheat and pea leaves also likely inhibited their ability to intercept the foliar applied spray of KH_2PO_4 dissolved in water.

The observed response of wheat to foliar P in this study appears to be lower in magnitude compared to some previous research (Mcbeath et al., 2011; Pierce et al., 2014). Overall, there is no indication in the current study that foliar KH_2PO_4 application efficacy is similar to seed placed MAP efficiency for wheat, and instead indicates that it is less effective. This could be due to difference in timing of application compared to other studies. However, the elevated canola and wheat grain P concentrations and uptake (Table 3.4) suggest that a portion of seed-placed P absent at germination can be replaced in the plant by foliar K_2PO_4, and grain P concentrations comparable to seed-placed MAP can be achieved. However, there may be a yield penalty if the P is applied too late. For addressing P deficiency by a mid- season application, foliar K_2PO_4 was unable to replace the lost yield potential from lack of starter seed-placed P and its benefits in early nutrition. Foliar P replaced some of the lost uptake. In this case it would appear foliar K_2PO_4 had a greater effect on grain quality (P content) than yield. In reference to previous studies, the aforementioned glasshouse experiments primarily focused on application of foliar P as H_3PO_4 while this study used KH_2PO_4 along with a surfactant. Foliar P form and additive is likely to influence performance along with crop, soil and environmental conditions. A comprehensive comparison of multiple foliar P products was not within the scope of this study, and therefore the efficacy of K_2PO_4 versus PA cannot be commented on. Both P and K are phloem mobile in the plant and can move from organs of relative surplus to growing tissues to reduce the effects of deficiency growth when nutrient demand is greater than uptake (Fernandez et al., 2013). The potential for re-mobilization of foliar-absorbed nutrients is low until the potential binding sites for that nutrient within the leaf become saturated. As such, nutrient deficiency reduces nutrient mobility due to surplus binding sites that hold the P in place (Fernandez et al., 2013).

Due to the greater surface area of the canola leaves compared to pea and wheat, a greater proportion of the foliar spray applied was observed to land on the leaf, instead of falling to the soil surface. Foliar P efficacy is a function of plant P demand and leaf interception of foliar fertilizer (Pierce et al., 2014), and interception is thus a function of leaf morphology and application method (spray vs drip). A crop with many horizontally oriented, broad and cupping leaves such as canola can also be expected to have more stomata in a position to allow liquid to enter, which has been identified as a significant uptake pathway (Eichert, 1998; Fernandez et al., 2005). A photo (Fig. 3.6) shows canola and wheat plants 24 hrs after foliar P application, in which KH_2PO_4 salt residue can be seen adhered to the leaves. McBeath et al. (2011) reported high stem P variability making it difficult to identify actual plant uptake and assimilation of foliar P fertilizer into the interior of the plant. Plant tissue was not washed prior to analysis in this study due to risk of loss of water soluble P from the interior of the tissue (McBeath et al., 2011). However, since the trays in the chamber were watered from the top of the tray without any water passing over the leaves, it is possible that some foliar applied P remains on the exterior of the leaf for some time. Previous research in wheat has involved application of foliar P at Zadoks stage 39 (flag leaf) (Mcbeath et al., 2011) and Zadoks 55 (ear emergence) and 65 (mid-anthesis) (Pierce et al., 2014), compared to the current study which was Zadoks 37 (flag leaf emergence) (Zadoks et al. 1974). This gives more time for absorption and redistribution. High proportions of P are redistributed and translocated to the grain during anthesis (Grant et al., 2001) and the proportion of foliar P translocated has been seen to be reduced as rate increases during very late season applications (Pierce et al., 2014). Foliar ammonium phosphate application has been observed to remedy deficiency in wheat as early as 20-25 d. after seeding (Haloi, 1980) but is likely less effective when application is delayed. Plant response to P is a response to increased photosynthetic capacity, producing more carbohydrates that are later translocated to the grain during senescence (Chapin and Wardlaw 1988). The potential of pre-anthesis foliar application would be to maximize P accumulation in vegetative growth while those cells are importing nutrients before they become source cells. There may be a fairly wide window of response to foliar P in wheat, with greater P demand and translocation associated with anthesis (Benbella and Paulsen, 1998; Grant et al., 2001; Mcbeath et al., 2011; Pierce et al., 2014) that also might suggest later season application of foliar P to be more appropriate. However, recovery of applied P can further be reduced by senescence (Pierce et al., 2014) and translocation to roots (McBeath et al., 2011).

Figure 3.6: Canola (left) and wheat (right) leaves 24 hrs after foliar KH_2PO_4 application. Note fertilizer salt residue is observed on the adaxial leaf surface.

The presence of residual fertilizer on the exterior of the leaves might account for increased canola straw P content measured at the end of the growing season in the F(100) treatment (Table 3.4). However the comparable canola grain yield and P contents of the fertilized treatments suggests that translocation of foliar applied P from leaf tissue to grain was occurring. Considering the trays used had limited volume of soil and each fertilizer treated pot received equivalent rates of N, P and K fertilizer, if foliar P was completely ineffective then only the SP (and to a lesser degree F(50)) treatment would have sufficient P levels (via soil application) to match available soil N levels. The restricted root volume in controlled environment studies increases the likelihood of plants utilizing all available nutrients without contributions from other soil P pools found in the large soil volumes in the field. The soil in the F(100) was the most nutritionally P imbalanced at the beginning of the growth period as it only received starter N and did not receive P until later in the season, yet in canola, the P uptake was similar to the SP treatment (Table 3.4). Regardless of the lack of starter P, canola appeared to utilize foliar applied P under early soil P deficient conditions with adequate soil N. The results of the controlled environment indicate that a small amount of foliar uptake did occur which can improve canola yields compared to no fertilizer P. However, under field conditions where root growth in spring can be inhibited by a multitude of factors such as cold temperature and growing seasons can be short, the contribution of spring soil applied P in terms of providing early supply is likely more essential in the field. Studies under field conditions are considered in the next section of this chapter.

3.5.3.2 *Field studies*

The *P* values for the straw and grain yield and the grain and straw P uptake for all P trial sites in 2016 and 2017 are shown in Table 3.5. Of the sites and years evaluated in this study, the Pilger site was most responsive to soil versus foliar application P treatment, consistent with this site having low soil P fertility according to soil test (see Table 3.3) and relatively good growing conditions that year. Overall, across the sites, 2016 generally had better growing season moisture (see Table 3.2) than 2017, where drought limited yield, especially for canola and pea in the southern Saskatchewan sites located at Central Butte and Mawer (Table 3.6). Some issues with pests in specific crops occasionally arose such as cutworm injury in wheat at the Pilger site in 2016, and some bird damage to wheat and pea at the Mawer site in 2017. Responses are discussed on a site by site basis in the following sections.

Table 3.5: *P* values for treatment effect on grain yield, straw yield, and grain and straw P uptake using Tukey's protected HSD for fixed effect in the P fertilization field trials conducted in 2016 and 2017 (α=0.10).

Site (Association)	Effect	Numerator df	Variable† Straw Yield 2016	Straw Yield 2017	Grain Yield 2016	Grain Yield 2017	Straw P 2016	Straw P 2017	Grain P 2016	Grain P 2017
Pilger (Krydor)	Crop	2	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**0.0051**	**<.0001**
	Treatment	4	**0.0007**	0.1982	**<.0001**	0.1566	0.9417	**0.0581**	**0.0005**	0.2516
	Crop*Treatment	8	**0.0008**	0.7634	**<.0001**	0.2988	0.2927	0.696	**0.0010**	0.3514
Central Butte (Echo)	Crop	2	**<.0001**	**<.0001**	**0.0515**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
	Treatment	4	**0.0675**	0.8240	0.5955	0.9784	0.8502	0.6357	0.7600	0.8933
	Crop*Treatment	8	**0.0407**	0.5380	**0.0557**	0.5323	**0.0700**	0.7966	0.2927	0.4474
Rosetown (Sutherland)	Crop	2	**<.0001**	*NT*	**<.0001**	*NT*	**<.0001**	*NT*	**<.0001**	*NT*
	Treatment	4	0.1036	*NT*	0.9619	*NT*	0.5239	*NT*	0.9232	*NT*
	Crop*Treatment	8	**0.0017**	*NT*	0.3883	*NT*	0.3920	*NT*	0.7010	*NT*
Mawer (Weyburn)	Crop	2	*NT*	**<.0001**	*NT*	**<.0001**	*NT*	**<.0001**	*NT*	**<.0001**
	Treatment	4	*NT*	0.4880	*NT*	0.7607	*NT*	0.1239	*NT*	0.3902
	Crop*Treatment	8	*NT*	**0.0584**	*NT*	0.5609	*NT*	**0.0011**	*NT*	0.1688

† Variables containing *NT* indicate no trial was conducted at that site that year. Bolded values are significant at *P*<0.10.

Table 3.6: Straw and grain P uptake and yield at 2016 and 2017 foliar P fertilizer trials.

Site (Soil Association)	Crop	Treatment†	Variable							
			Straw P		Grain P		Straw Yield		Grain Yield	
			2016	2017	2016	2017	2016	2017	2016	2017
			——————————————— kg ha^{-1} ———————————————							
Pilger (Krydor)	Canola	C	0.6b‡	0.9§	4.1b	10.7c	3283c	2448b	1322c	1365b
		SP	1.4a	1.1	13.8a	14.1ab	8117a	3387a	4966a	1856a
		F(25)	0.9ab	1.0	6.3b	14.8a	5029b	3371a	2184b	1877a
		F(50)	1.1ab	1.0	6.2b	13.0a	4839b	2838ab	2181b	1646ab
		F(100)	1.2a	1.0	6.0b	11.9bc	4263bc	2728ab	2177b	1590ab
	Pea	C	2.8	1.3ab	8.6	6.1b	3565	1723ab	3120ab	1373b
		SP	2.3	1.5ab	8.3	8.9a	3416	2032ab	2990ab	1795a
		F(25)	2.5	1.8a	8.9	6.8ab	3580	2266a	3160ab	1335b
		F(50)	2.4	1.2b	9.3	5.8b	3700	1480b	3500a	1159b
		F(100)	2.3	1.4ab	7.4	7.3ab	3114	1897ab	2281b	1417b
	Wheat	C	1.8	0.3b	5.4	3.1	3190	775	1495	539
		SP	1.9	0.5b	7.2	5.4	3761	1273	1967	939
		F(25)	2.1	1.4a	6.4	3.2	3193	846	1772	512
		F(50)	1.9	0.3b	6.8	3.4	2907	751	1818	566
		F(100)	1.8	0.5b	5.4	4.2	3093	1144	1482	714
Central Butte (Echo)	Canola	C	1.4	1.9	22.1a	10.9b	8005ab	2438ab	4470a	863ab
		SP	1.2	2.4	17.7ab	10.8b	6739bc	2480ab	3656ab	851ab
		F(25)	1.2	2.4	16.0b	14.0a	6501c	2826a	3069b	1072a
		F(50)	1.4	2.4	20.0ab	10.8b	8867a	2566ab	4680a	835ab
		F(100)	1.8	2.2	22.5a	9.7b	5504c	2196b	4658a	727b
	Pea	C	3.1a	2.0ab	13.3	5.1	4619	1480ab	4976	793
		SP	2.1b	2.9a	11.6	6.2	3884	2022a	4203	976
		F(25)	2.7ab	1.8b	12.1	5.0	4262	1297b	4468	752
		F(50)	2.8a	2.0ab	12.8	5.5	4371	1525ab	4484	836

		F(100)	2.8a	2.2ab	12.4	7.0	4457	1783ab	4709	1063
	Wheat	C	1.0b	0.9	10.2	13.0	3990b	2100	3045b	2038
		SP	1.7a	0.8	14.5	12.8	6090a	2163	4580a	1989
		F(25)	1.6ab	0.7	13.0	12.6	5161ab	2197	3902ab	2080
		F(50)	1.6ab	0.8	15.1	13.7	5607a	2277	4468a	2163
		F(100)	1.3ab	0.8	10.9	11.7	4205b	2032	3170b	1945
Rosetown (Sutherland)	Canola	C	2.4ab	NT¶	27.3ab	NT	8272a	NT	4956a	NT
		SP	1.9bc	NT	22.9b	NT	6262b	NT	3474b	NT
		F(25)	1.4c	NT	25.4ab	NT	5995b	NT	4463ab	NT
		F(50)	2.2abc	NT	26.0ab	NT	6366b	NT	4770a	NT
		F(100)	2.7a	NT	30.8a	NT	8800a	NT	4544ab	NT
	Pea	C	3.00	NT	14.7	NT	4297	NT	4628	NT
		SP	3.2	NT	17.0	NT	4976	NT	5154	NT
		F(25)	2.7	NT	14.4	NT	4143	NT	4866	NT
		F(50)	3.3	NT	15.2	NT	4334	NT	4876	NT
		F(100)	2.9	NT	16.0	NT	4466	NT	5326	NT
	Wheat	C	2.8	NT	12.0	NT	5758	NT	3360	NT
		SP	3.3	NT	13.7	NT	6372	NT	3718	NT
		F(25)	3.3	NT	12.4	NT	5776	NT	3269	NT
		F(50)	3.6	NT	12.0	NT	5737	NT	3223	NT
		F(100)	3.3	NT	11.6	NT	5597	NT	3208	NT
Mawer (Weyburn)	Canola	C	NT	2.5bc	NT	23.8a	NT	3937a	NT	1792a
		SP	NT	2.7b	NT	19.3bc	NT	3257bc	NT	1495ab
		F(25)	NT	3.5a	NT	21.5ab	NT	3516ab	NT	1502ab
		F(50)	NT	2.0c	NT	17.6c	NT	2873c	NT	1325b
		F(100)	NT	3.0ab	NT	23.6a	NT	3885a	NT	1783a
	Pea	C	NT	1.3b	NT	4.0	NT	1367b	NT	591
		SP	NT	2.7a	NT	6.1	NT	1668ab	NT	731
		F(25)	NT	1.6b	NT	5.6	NT	1584ab	NT	808
		F(50)	NT	2.9a	NT	6.3	NT	1955a	NT	783
		F(100)	NT	2.6a	NT	6.3	NT	1836ab	NT	790

Wheat	C	NT	0.6	NT	7.2	NT	1044	NT	946
	SP	NT	0.5	NT	6.0	NT	1010	NT	883
	F(25)	NT	0.5	NT	7.9	NT	1203	NT	1123
	F(50)	NT	0.7	NT	7.6	NT	1092	NT	1073
	F(100)	NT	0.8	NT	8.0	NT	1213	NT	1100

† Treatments labelled C, SP, F(25), F(50) and F(100) denote unfertilized control, all (100%) seed placed P, 75% applied as seed-placed and 25% applied as foliar, 50% P applied as seed-placed and 50% as foliar, and 100% P applied as foliar respectively. All fertilized treatments received a total of 20 kg P_2O_5 ha^{-1}.

‡ Means were separated using Tukey's HSD. Means with same letter within same crop, site, column and year are not significantly different (α=0.10).

§ No letters denotes no significant differences (α=0.10).

¶ NT denotes no trial was conducted at that site that year.

Pilger Site: Krydor Association

The Pilger site soils had the lowest P fertility according to soil test (Table 3.3), consistent with rates of P fertilizer application made by the grower over the years that were much less than crop removal. Comparing the 2016 grain and straw yield as well as P uptake at the Pilger site (Table 3.6), of the three crops evaluated canola was the most responsive to treatment as it displayed significant differences among all parameters except 2017 straw yield (P<.0001). This is consistent with results from the controlled environment studies (see section 3.3) in which the Pilger site Krydor association soil was also most responsive. For canola grain yield, the SP treatment produced significantly (P<0.10) greater yield than all other treatments followed by the F(25), F(50) and F(100) respectively, which were significantly greater than the C treatment. Higher proportions of P fertilizer applied with the seed appeared to favor higher canola yield and P uptake in both 2016 and 2017. Grain P uptake was greatest in canola in the SP treatment which was significantly greater than all other treatments. Overall, canola had the highest grain P content followed by pea, with wheat the lowest. Straw yield and P uptake followed a similar pattern to grain yield. For all crops, the majority of the above-ground P content was found in the grain. Annual crops have most of their above-ground P content (>70%) in grain at maturity (Havlin et al., 2014).

Pea grain yield at Pilger responded positively to P fertilization only in 2017 and, like canola, only when all the P was seed-placed. The response diminished when some or all of the P was foliar applied. In 2016, there was no positive grain yield response of pea to P fertilization and the lowest pea yield, lower than the unfertilized control, was observed in the 100% foliar P treatment. This suggests that some injury to pea may have occurred when all 20 kg P_2O_5 ha^{-1} was applied as foliar spray. The setback in yield observed by the F(100) treatment could be caused by foliar burn as a result of increased salt-load on the leaf (Pierce et al., 2014). However, we did not observe any marked foliar injury symptoms on the pea when the site was visited one week after application, although symptoms may have manifested and disappeared during the week between time of application and time of sampling. Correlations between severe leaf burn and reduced yields have been reported (Parker and Boswell 1980), but others have found burn symptoms to have no association with crop yield (McBeath et al. 2011; Phillips and Mullins 2004). Foliar burn can be induced by dissolved fertilizer applied in low water volumes over a small leaf surface area that produces injury from increasing acidity (pH <2) and/or salt concentrations (Pierce et al., 2014). Pea is also a relatively effective scavenger for soil P and, as such was expected to be less responsive to added P fertilizer in general due to acidification of the rhizosphere and the strong mycorrhizal relationships they develop, enhancing their ability to access native soil P and reducing their requirement for added P fertilizer (Hinsinger, 2001). This may explain the lack of difference between the control and SP treatment in which fertilizer application had no significant effect on yield.

Wheat yield and P uptake was not significantly affected by treatment at the Pilger site both years, which may be attributed to some significant cutworm pressure on this crop. However, wheat showed a pattern in yield and P uptake response to P fertilization treatment that was similar to that observed with canola and pea: higher proportion of P in seed-placed form favored yield and above-ground crop P content.

In general, among yield parameters at the P deficient Pilger site there is an apparent decrease in production when proportion of P applied as seed placed P fertilizer is reduced and the proportion applied as foliar is increased. However the finding that the F(100) grain treatment was sometimes higher than the unfertilized control treatment suggests that some degree of uptake and physiological benefit from the foliar P was occurring, though in this study we cannot determine whether this contribution to yield was related to uptake occurring through leaf material or the soil.

Overall, the findings point towards less uptake and efficiency in producing yield when proportion of P applied in foliar form is high (e.g. 50% or greater). Foliar P fertilizer that is applied later may not all be translocated through the plant, or used as efficiently as seed placed MAP taken up through the roots.The KH_2PO_4 foliar spray is intended to add P and it adds K, while the seed-placed MAP is intended to add P and it adds N. In the field trials, adjustment was made for the N added in MAP in the basal application of N fertilizer so all treatments received the same amount of N, and the basal blanket application of K fertilizer made across all plots and high inherent K fertility of the soils means that the effects observed are mainly attributable to P.

Phosphorus (P) concentrations were measured mid-season in the P treatments where 25%, 50% and 100% of the 20 kg P_2O_5 ha^{-1} rate was applied as foliar P, along with the unfertilized control to help determine the effectiveness of the applications on plant P nutrition (Table 3.7). Mid-season above ground plant samples were taken before and one week after foliar P application and samples measured for P concentration (Table 3.7). Plants were sampled 1 week after foliar P treatments to allow time for the proportion of foliar P that is adhered to the surface of the plant leaves and not absorbed to be reduced. The seed-placed P fertilizer in the F(25), F(50), F(100) treatments is 15, 10, and 0 kg P_2O_5 ha^{-1} along with foliar P fertilization at 5, 10 and 20 kg P_2O_5 ha^{-1} respectively. The plant tissue P concentrations prior to foliar P application generally reflect the effect of the added seed-placed P on increasing soil P availability. With similar or increasing concentration of P in the plant with more P fertilizer added at the time of seeding (Table 3.7). Compared to pre-application concentrations, the P concentrations measured after foliar application will be influenced by plant growth with dilution over the one week period tending to lower the P concentration in the tissue. Greater rates of P added in foliar form would be expected to increase concentration. Therefore, a reduced decrease or greater increase (change) comparing before and after application reflects greater P on or inside the plant material. The mid-season above-ground plant tissue samples analyzed for P concentration at Pilger (Table 3.7) in 2016 canola showed no significant difference for P content before or after, or for total change in concentration. In 2016, the F(50) and F(100) treatments showed a mean increase in P concentration while in pea the concentration decreased in the foliar treatments, perhaps reflecting injury which reduced uptake. The change in concentration from pre-application to post-application followed a similar trend in wheat as in canola. When comparing the canola yield data, the increase in tissue P concentration suggests uptake of foliar spray through leaf tissue may have occurred as F(50) and F(100) yields were significantly greater than C yield. However the control treatment had the same P concentration as the foliar treatments at time of post application sampling, making it difficult to separate contributions from the foliar fertilizer or the soil.

Table 3.7: 2016 and 2017 Pilger field site mid-season above-ground plant tissue P concentration pre- and post-foliar P application treatment and the change (Δ) in tissue P concentration.

Crop	Treatment†	——————2016——————			——————2017——————		
		Pre-App	Post-App	Δ	Pre-App	Post-App	Δ
		——————————mg kg-1——————————					
Canola	F(25)	2751‡	2572§	(-)179	2433	1498	(-)935
	F(50)	2460	3054	(+)593	2638	1452	(-)1186
	F(100)	2351	2837	(+)486	2444	1565	(-)879
	C¶	2351	2919	(+)568	2444	1386	(-)1058
Pea	F(25)	2452	2408a	(-)44a	2934	2488a	(-)446
	F(50)	2822	1636b	(-)1186b	2906	1982b	(-)924
	F(100)	2465	2108ab	(-)357a	2684	1945b	(-)740
	C	2465	2414a	(-)51a	2684	1765b	(-)919
Wheat	F(25)	3178a	2916	(-)263	2582	2107	(-)475
	F(50)	2517b	2721	(-)204	2511	2224	(-)287
	F(100)	2460b	2424	(-)36	2557	2131	(-)426
	C	2460b	2426	(-)34	2557	1972	(-)585

† Treatments labelled F(25), F(50) and F(100) and C denote 75% applied as seed-placed and 25% applied as foliar, 50% P applied as seed-placed and 50% as foliar, and 100% P applied as foliar, and unfertilized control respectively. All fertilized treatments received a total of 20 kg P_2O_5 ha^{-1}.

‡ Means with same letter within same crop within same column are not significantly different (α=0.10).
§ No letters indicates no significant difference (α=0.10).
¶ As the F(100) and Control plots received the same treatment up until foliar P application, the control values are estimated to be comparable to F(100).

Central Butte Site: Echo Association

In 2016, the Central Butte, Echo association soil showed a significant treatment effect on yield and crop in straw and grain P uptake and straw and grain yield, depending on crop (Tables 3.5 and 3.6). At this site, canola in 2016 showed a slight reduction in grain yield with greater proportion of fertilizer P applied with the seed. Treatments F(25) and SP were the lowest yielding but only F(25) was significantly lower than the control treatment (Table 3.6). For canola straw yield the F(25) and F(100) treatments resulted in significantly less straw biomass production than the C and F(50) treatments. The reduction in yield observed in 2016 with the seed-placed P may reflect injury, as conditions were relatively dry in early May immediately after seeding that produced patchy germination and emergence early on. However, rains later in May and throughout the season contributed to compensation and overall very good canola yields (3000-4500 kg ha^{-1}). In 2017, canola yields were greatly impacted by dry conditions later in the growing season, with grain yields <1000 kg ha^{-1} at this site. The 2017 canola grain yield results showed the F(25) treatment to produce the greatest grain yield but it was only significantly greater than the F(100) treatment. There were no positive significant responses of canola yield to P fertilization at the Central Butte site in either 2016 or 2017, reflecting sufficient supplies of soil P at this site which are consistent with its history of use of moderate rates of applied P (~20 kg P_2O_5 ha^{-1}) annually, and relatively low crop removal over the years due to generally moisture limited conditions. Canola P uptake followed similar trends to grain yield, with significantly higher grain P uptake in 2017 in the F(25) treatment than the other treatments. This suggests that under the dry 2017 growing conditions at this site, 15 kg P_2O_5 ha^{-1} with the seed and a top-up with 5 kg P_2O_5 ha^{-1} as foliar applied P resulted in best plant P utilization of the 20 kg P_2O_5 ha^{-1} rate. This provides some support to the concept of foliar P being more beneficial under adverse growing conditions such as dry soil that may limit P movement by diffusion and also root growth.

The effects of P fertilization on pea yields and plant P uptake in grain and straw at this site were small and the only significant treatment effects were observed in the 2017 straw pea straw. The pea straw P was greatest in the C, F(100) and F(50) treatments which were significantly greater than the SP treatment. Foliar application appeared to increase straw P in this crop and little else, as the pea showed no response to treatment among the remaining variables in 2016 or 2017. Lack of significant response is consistent with the higher P fertility at the Central Butte location compared to Pilger, and ability of legumes to effectively scavenge and use P that is already present in the soil.

Wheat grain and straw yields in 2016 (Table 3.6) were greatest in the SP and F(50) treatments which were significantly greater than the C and F(100) treatments, indicating better performance when some P is applied with the seed at seeding. Foliar P application did not significantly affect grain P uptake but was higher when some of the P was applied with the seed at the time of seeding. For straw P uptake, the SP treatment resulted in the greatest straw P uptake that was significantly greater than the control treatment. In 2017 P fertilizer application had no significant effect on wheat grain and straw yields with similar yields among all treatments and depressed relative to 2016 yields as a result of dry conditions in the latter part of the growing season.

Foliar P rates of 2 kg P_2O_5 ha^{-1} applied sequentially at tillering, boot and anthesis, in conjunction with 20 kg P_2O_5 ha^{-1} seed-placed P was reported to significantly increase wheat yields compared to only seed placed P (Samad et al., 2014). It has been reported that 16 % of foliar applied P was taken up in the first 2 hrs following application on soybean (Barrier and Loomis, 1957), and a period of only 2 d. after application was past the rapid initial uptake phase (Bouma, 1969). This might account for the strength of the F(25) and F(50) wheat yields relative to SP in which reduced rates of seed-placed MAP were offset by foliar P application resulting in comparable grain yields. In this case, had a low rate of foliar P been applied in addition to the SP treatment, even greater yields may have been achieved. The observation that the F(100) treatment in which all 20 kg P_2O_5 ha^{-1} was applied as foliar P mid-season was unable to remedy P deficiency, supports the concept that a limited amount of P can be taken up through the leaves. As P uptake occurs in small quantities or rapid time frames, a multi-time treatment approach may provide more opportunities for P uptake through leaf tissue than a single application. However the potential time and cost requirements of multiple applications may be disadvantageous relative to yield benefit, especially if significantly more foliar P uptake is occurring after anthesis (Benbella and Paulsen, 1998).

Table 3.8 provides the Central Butte site mid-season above-ground plant tissue P concentrations before and after foliar P application. In 2016, the canola F(25), F(50) and F(100) treatments showed no significant difference in P concentration prior to foliar P application, but post-foliar P fertilizer application above-ground canola P concentration increased with increased proportion of P applied in foliar form and the canola F(100) treatment had the greatest P concentration which was significantly greater than the control treatment. In 2017, foliar P treatments in canola showed a decrease in mid-season above-ground biomass P concentration with increasing proportion of P applied in foliar form. This same significant effect was also observed in the pea in 2017. Dry conditions may favor seed-placed P for uptake due to reduced diffusion rates (Havlin et al., 2014) and also possibly limiting the uptake of P through the leaves via closed stomata. In contrast to canola and pea, wheat mid-season P concentrations were similar among treatments and not significantly affected by proportion of P applied as foliar mid-season versus applied with the seed at seeding in either 2016 or 2017.

Table 3.8: 2016 and 2017 Central Butte field site mid-season above ground plant tissue P concentration pre- and post-foliar P application treatment and the change (Δ) in tissue P concentration.

Crop	Treatment†	——————2016——————			——————2017——————		
		Pre-App	Post-App	Δ	Pre-App	Post-App	Δ
		————————————mg kg^{-1}————————————					
Canola	F(25)	3791‡	3350ab	(-)441	2464	1922a	(-)542
	F(50)	3797§	3444ab	(-)353	2460	1535c	(-)924
	F(100)	3646	3782a	(+)137	2463	1670bc	(-)793
	C¶	3646	3209b	(-)437	2463	1803ab	(-)660
Pea	F(25)	3192a	2803	(-)389	2251a	1590a	(-)661
	F(50)	3039ab	2897	(-)142	1782b	1436ab	(-)346
	F(100)	2589b	2882	(+)293	2112ab	1315b	(-)798
	C	2589b	2476	(-)113	2112ab	1631a	(-)481
Wheat	F(25)	1770b	2142	(+)371	1795	1150	(-)645
	F(50)	2484a	2237	(-)247	1873	1339	(-)534
	F(100)	2175ab	2154	(-)21	1771	1214	(-)557
	C	2175ab	2042	(-)133	1771	1105	(-)666

† Treatments labelled F(25), F(50) and F(100) and C denote 75% applied as seed-placed and 25% applied as foliar, 50% P applied as seed-placed and 50% as foliar, and 100% P applied as foliar, and unfertilized control respectively. All fertilized treatments received a total of 20 kg P_2O_5 ha^{-1}.
‡ Means with same letter within same crop and column are not significantly different (α=0.10).
§ No letters indicates no significant difference (α=0.10).
¶ As the F(100) and Control plots received the same treatment up until foliar P application, the control values are estimated to be comparable to F(100).

Rosetown Site: Sutherland Association

In the Rosetown site field trial, conducted in the 2016 growing season on soil mapped as Sutherland association, canola was the only crop that showed significant response to the P fertilization treatments, with a significant crop by treatment interaction (Table 3.5 and Table 3.6) for straw yield. A significant response in canola was observed in grain and straw yield as well as grain and straw P uptake to treatment. For grain yield, the C and F(50) treatments produced the greatest yield, which were only significantly greater than the SP treatment, which had the lowest yield. A similar trend to yield was observed in the canola P uptake. The lack of positive response to P fertilization and the depression of yield and P uptake in the seed-placed P treatment in the canola is explained by the history of P application at recommended rates by the grower (~20 to 30 kg P_2O_5 ha^{-1}) and use of no-till over a number of years at this site, resulting in good soil P fertility. Uneven germination and emergence was observed with the seed-placed P treatment in canola at this site, similar to the Central Butte site due to dry conditions in early spring, which may have contributed to reduced yield. Under these conditions, a reduced proportion of P applied as seed-placed and an increased proportion in foliar form appeared to be of benefit for the canola. At the Rosetown site, there was no significant response of pea or wheat to P fertilization treatment (Table 3.6), with similar yields and P uptake among all treatments. The yield and uptake results from the Rosetown sites do not indicate additional uptake of soil or foliar applied fertilizer P under conditions of high soil P availability. Growing conditions during the season at Rosetown were considered good but the available P in the Sutherland association soil was not likely deficient enough to elicit a response to foliar P. This is consistent with other research that indicates growth promoting environmental conditions that increase crop P demand along with soil P deficiency conditions are contributors to increasing foliar P fertilizer efficacy (Al Harbi et al., 2013; Silberbush, 2002).

The mid-season above ground canola plant tissue P concentrations at the Rosetown site (Table 3.9) were not significantly different among treatments, but there were significant differences in the change in concentration, suggesting an increase in plant P arising from the foliar application in the canola. This effect was also observed in wheat, with effects more variable in the pea. Therefore there is some evidence for foliar P at least residing on the surface of the leaf following application, if not taken up into the interior of the plant. However, given the similarity and lack of any significant effect on straw or grain content at harvest in the treatments compared to the unfertilized control, the foliar applied P may have simply washed off over the season. If P had been translocating to the roots at time of application, a surplus of P binding sites in the leaf may have been present, increasing the absorption potential of the leaf surface (Fernandez et al., 2009). In wheat and canola it would appear that some uptake occurred through leaf tissue but there was no notable change in agronomic factors to discern foliar P fertilizer as having equal or greater efficacy than seed placed MAP.

Table 3.9: 2016 Rosetown field site mid-season above ground plant tissue P concentration pre- and post-foliar P application treatment and the change (Δ) in tissue P concentration.

Crop	Treatment†	Pre-App	Post-App	Δ
		—————————	mg kg^{-1}	—————————
Canola	F(25)	4837‡	3812	(-)1025b
	F(50)	4584§	3724	(-)860ab
	F(100)	4539	4234	(-)305a
	C¶	4539	3745	(-)794ab
Pea	F(25)	3426	3312a	(-)114
	F(50)	3480	2767b	(-)713
	F(100)	3614	3277ab	(-)338
	C	3614	2892ab	(-)722
Wheat	F(25)	3614	2864	(-)751b
	F(50)	3906	3370	(-)536ab
	F(100)	3493	3370	(-)123a
	C	3493	3056	(-)437ab

† Treatments labelled F(25), F(50) and F(100) and C denote 75% applied as seed-placed and 25% applied as foliar, 50% P applied as seed-placed and 50% as foliar, and 100% P applied as foliar, and unfertilized control respectively. All fertilized treatments received a total of 20 kg P_2O_5 ha^{-1}.
‡ Means with same letter within same crop and column are not significantly different (α=0.10).
§ No letters indicates no significant difference (α=0.10).
¶ As the F(100) and Control plots received the same treatment up until foliar P application, the control values are estimated to be comparable to F(100).

The critical concentration of tissue P for deficiency in wheat measured mid- season was reported by Green and Racz (1999) to be 0.3 % w/w (3000 mg kg^{-1}) (Green and Racz, 1999). The wheat tissue samples taken at Rosetown prior to treatment were greater than 0.3 % w/w which may explain the lack of response. Conversely, the 2016 Pilger and Central Butte wheat tissue samples collected were lower than the critical value and tissue P concentration declined after treatment, similar to Rosetown. The only increase in wheat tissue P occurred in tissue samples measuring below 2000 mg P kg^{-1}. It is possible that canola at the Pilger site was so severely deficient that it required more than 20 kg P_2O_5 ha^{-1}, in which case 20 kg P_2O_5 ha^{-1} placed with the seed in addition to mid-season foliar P application may be needed to maximize response and yield in canola under the conditions at Pilger in 2016. Foliar P fertilizer application as a supplement to seed placed P as opposed to a replacement has been suggested by Pierce et al. (2014) who found more than 90 % of P residing in the ear of wheat to be sourced from the soil fractions. Furthermore, foliar KH_2PO_4 uptake efficiency in wheat has been suggested to be maximized at rates of 2 kg P_2O_5 ha^{-1} with decreasing efficiency with increasing rate (Benbella and Paulsen, 1998; Mohali et al., 2006). Therefore, a small amount of foliar P (<5 kg P_2O_5 ha^{-1}) as a top-up in highly P deficient soils, especially for canola, but also possibly wheat as well in highly deficient soils could be beneficial, but is not a substitute for soil applied P at the time of seeding.

Mawer Site: Weyburn Association

In the 2017 Mawer site Weyburn association soil, significant interaction between crop and treatment was observed in in straw yield but not grain yield (α=0.10) (Table 3.5). No significant treatment effect was observed in grain and straw yield but crop effect was significant across both variables. Significant crop by treatment effect was apparent for straw P content.

The 2017 season was much drier than normal at the Mawer site. Canola grain yield and P uptake (Table 3.6) followed a pattern similar to that observed at the Rosetown site, with no positive response to P fertilization and some evidence for yield depression when all the P was seed placed, again perhaps reflecting some negative effect of delayed germination and emergence of the canola. Yields of all three crops were low (<1700 kg ha^{-1}), a consequence of hot, dry conditions especially in July in 2017, which would have reduced crop P demand. The F(100) and C treatments produced the greatest canola grain yield (Table 3.6) with a similar trend for canola straw yield. The P contained in the canola straw at harvest was generally increased by P fertilization, with the highest straw P uptake in the F(25) treatment which also produced the highest canola straw biomass.

Pea straw yield tended to respond positively to P fertilization at the Mawer site as did grain yield. Hot, dry conditions in early July at flowering and pod formation likely contributed to the low pea grain yields observed relative to straw production. Wheat yields were low and similar among all treatments at this site. The wheat and pea also suffered some damage from blackbird flocks. Across all crops at the Mawer 2017 site, the high rate foliar P treatment (F(100)) resulted in the greatest grain P uptake but was only significantly greater than the SP treatment. Significant positive response was measured in canola (P=0.0114) and pea (P=0.0005) straw P content at the Mawer 2017 site.

The mid-season plant tissue P concentrations in Table 3.10 show no significant differences in P concentration amongst treatments until after foliar P treatment (Post-App). At this site in 2017, the sampling was delayed by about six d. compared to the other sites, explaining the lower concentrations of plant material as a result of further growth dilution. Across canola, pea and wheat, all tissue concentrations decreased between sampling periods. For canola and pea, foliar P application generally increased the P concentration measured in collected plant tissue, while, interestingly, in wheat it appeared to result in a decrease. Overall, foliar P application had little effect on P content among all three crops nor did a trend consistently favor foliar or seed-placed P fertilizer. Lack of significant results may be due to limited uptake caused by dry weather or rapid uptake and mobilization of applied P fertilizer to somewhere else (e.g. roots) that occurred between sampling periods (Barrier and Loomis, 1957; Bouma, 1969).

Table 3.10: 2017 Mawer field site mid-season above ground plant tissue P concentration pre- and post-foliar P application treatment and the change (Δ) in tissue P concentration.

Crop	Treatment†	Pre-App	Post-App	Δ
		——————————mg kg^{-1}————————————		
Canola	F(25)	2245‡	1637b	(-)608
	F(50)	2165§	1889a	(-)276
	F(100)	2257	1737ab	(-)520
	C¶	2257	1768ab	(-)498
Pea	F(25)	1594	1375a	(-)219
	F(50)	1745	1254ab	(-)492
	F(100)	1518	1356a	(-)161
	C	1518	1052b	(-)466
Wheat	F(25)	1671	1161ab	(-)457
	F(50)	1689	1000b	(-)690
	F(100)	1801	1247a	(-)554
	C	1801	1373a	(-)428

† Treatments labelled F(25), F(50) and F(100) and C denote 75% applied as seed-placed and 25% applied as foliar, 50% P applied as seed-placed and 50% as foliar, and 100% P applied as foliar, and unfertilized control respectively. All fertilized treatments received a total of 20 kg P_2O_5 ha^{-1}.
‡ Means with same letter within same crop within same column are not significantly different (α=0.10).
§ No letters indicates no significant difference (α=0.10).
¶ As the F(100) and Control plots received the same treatment up until foliar P application, the control values are estimated to be comparable to F(100).

Growth in 2017 was inhibited in large part by below-average spring and summer precipitation in southern Saskatchewan which would inhibit overall nutrient demand and uptake and potentially the capacity of crops to respond to P treatment. Drought reduces photosynthesis and therefore P demand, furthermore plants respond to drought with various mechanisms such as stomatal closure and increased diffusive resistance (Farooq et al., 2012). It might be anticipated that the foliar P spray applied would have less efficacy under these conditions as stomatal closure would potentially make movement into the leaf more difficult. However, the concentration of a nutrient in a foliar spray will always be significantly higher than found within plant organs and a concentration gradient will be established when a nutrient solution is applied to the plant surface, potentially promoting diffusion of that nutrient across and through the surface (Fernandez et al., 2013). Comparing efficacy of foliar P applied with different water volumes was not within the scope of this study, nevertheless water stress appeared to be a significant environmental factor affecting plant growth and response to foliar P application in 2017. The lack of response under moisture limiting conditions is consistent with findings of Denelan (1988) who noted reduced efficacy of foliar fertilizer under both drought and flooded conditions. Foliar P fertilizer application was made in the current study in July around mid-day when stomata are open to maximize the uptake potential of the stomatal pathway (Pierce et al., 2014) in addition to what would diffuse across the leaf cuticle. The stomatal pathway is dependent on more environmental factors than the cuticle (Noack et al., 2010) and is a more rapid process of uptake compared to slower cuticular penetration (Currier and Dybing, 1959). Higher average relative humidity values such as would occur under the wetter conditions of 2016 compared to 2017 will increase leaf permeability by cuticular hydration which delays the formation salts on the leaf surface and enhances the window of uptake (Fernandez et al., 2013). Considering that cooler air has a higher relative humidity, foliar P fertilizer efficacy may be increased if application was made during early morning when air temperature is relatively low allowing for a longer window of diffusion across the leaf cuticle and with stomata open.

3.5.4 Seed nutritional response to foliar P

3.5.4.1 *Zinc and iron concentrations*

There was a significant (α=0.10) crop effect for Zn concentration in the grain at the Pilger site in 2016, and significant crop, treatment and crop by treatment interaction for Fe (Table: 3.11). In 2017, there was a significant crop and treatment effect for Zn while only a significant crop effect was evident for Fe. At the Rosetown site, only the crop effect was significant for grain Zn and Fe concentration. The Central Butte site in 2016 had significant crop effect on Zn and Fe concentration and a significant crop by treatment effect on Zn concentration while in 2017 there were only significant crop effects. Crop effects were evident at the Mawer site but there were no significant treatment effects.

Among the three crops, the Zn concentrations in grain were greatest in wheat, ranging from ~ 30 to 50 mg Zn kg^{-1}, while pea had the highest Fe concentration that ranged from around 40 mg Fe kg^{-1} at the Pilger site to ~100 mg Fe kg^{-1} at the Rosetown site in 2016 (Table 3.12). Concentrations of Zn and Fe in the grain generally were higher in 2017 than 2016, which is explained by lower yields associated with the droughty conditions in 2017, with more growth dilution in 2016. The Zn concentrations in grain at Central Butte in 2016 were greatest in wheat and pea which were significantly greater than canola.

The greatest response to P fertilization treatment was observed at Pilger in canola ($P<.0001$), in which the treatment where all P was seed placed had the lowest Zn concentration. This can be explained by growth dilution, as canola responded to the greatest extent in yield increase to P fertilizer that was seed placed. In general, fertilization with P tended to decrease grain Zn and Fe concentrations that appears to be related to yield dilution. Pea was found to be the most responsive crop to P fertilization treatment in effects on Fe concentration in grain at the Central Butte ($P=0.0205$) and Rosetown ($P=0.0051$) sites, while canola ($P=0.0009$) and pea ($P<.0001$) were the most responsive at Pilger in 2016. Across all sites in 2016, the greatest Fe content was measured in pea which was significantly greater than both canola and wheat. On average the greatest Fe concentration was found in the control treatment, which was significantly greater than the SP treatment at the Central Butte site. Pea grain at Pilger in 2016 had significantly higher Fe concentration than canola and wheat, with the F(25) treatment generally resulting in significantly greater uptake than all other treatments across all crops. At Rosetown site, the F(100) treatment had the greatest Fe concentration in the peas.

Table 3.11: 2016 and 2017 foliar P field trial *P* values for treatment effect on grain Zn and Fe concentration using Tukey's protected HSD for fixed effect in Pilger site foliar P field trial in 2017 (α=0.10).

Site	Effect	Numerator df	Variable†			
			Zn		Fe	
			2016	2017	2016	2017
Pilger	Crop	2	**<.0001**	**0.0685**	**0.0218**	**<.0001**
	Treatment	4	**<.0001**	0.3626	**0.0203**	0.2101
	Crop*Treatment	8	0.2742	**0.0846**	**0.0033**	0.2546
Rosetown	Crop	2	**<.0001**	*NT*	**0.0015**	*NT*
	Treatment	4	0.9712	*NT*	0.3117	*NT*
	Crop*Treatment	8	0.2814	*NT*	0.103	*NT*
Central Butte	Crop	2	**<.0001**	0.3521	**<.0001**	**0.0311**
	Treatment	4	0.6656	0.6045	0.1084	0.5529
	Crop*Treatment	8	**0.0196**	**0.0148**	0.7484	0.6489
Mawer	Crop	2	*NT*	0.2652	*NT*	**<.0001**
	Treatment	4	*NT*	0.1960	*NT*	0.3567
	Crop*Treatment	8	*NT*	0.7235	*NT*	0.1608

† Variables containing NT indicate no trial was conducted at that site that year. Bolded values are significant at *P*<0.10.

As noted, at the 2016 Pilger site, canola grain Zn concentration was greatest in the C, F(50) and F(100) treatments which was significantly greater than the SP treatment (α=0.10) (Table 3.12). Although this effect may be explained largely by growth dilution, there may also be an antagonistic interaction between Zn uptake and soil applied P which has been reported in previous research (Lu et al., 2011; Ryan et al., 2008; Zhang et al., 2012). The trend in Fe concentration suggests that foliar P is beneficial to Fe concentration, but this may only be a consequence of a lower yield response when more P is added in foliar form. The Pilger 2016 site pea grain Zn concentration was also greatest in the unfertilized control which was significantly greater than the SP and F(25) treatments, indicating the same interaction between soil P and Zn uptake appearing to have occurred in pea as in canola. Foliar P application did not significantly affect pea Zn or Fe concentration, consistent with limited effect of P treatment on yield. Overall, application of P fertilizer, especially when all or a high proportion is applied in the seed-row at the time of seeding, results in lower concentration of the nutritional elements Zn and Fe in the grain. This impact is largely attributed to yield response and growth dilution from the added P, but may also reflect some antagonism between high levels of soil P and uptake of Zn by the plant as observed in previous research.

Table 3.12: Grain Zn and Fe concentrations in canola, pea and wheat in response to foliar P fertilization in all 2016 and 2017 foliar P field sites.

Site	Crop	Nutrient	2016 Treatment†					2017 Treatment				
			C	SP	F(25)	F(50)	F(100)	C	SP	F(25)	F(50)	F(100)
			mg kg^{-1}									
Pilger	*Canola*	Zn	31.5a‡	25.2b	28.4ab	29.3a	29.9a	31.8§	33.4	34.1	27.9	25.4
		Fe	36.6b	29.5b	28.9b	59.7a	46.3ab	74.3	77.5	66.2	70.9	63.6
	Pea	Zn	29.5a	25.5bc	23.1c	26.9ab	27.6ab	23.6	29.5	28.4	26.6	30.7
		Fe	48.9b	40.5b	89.9a	43.9b	45.7b	120.4a	79.6b	94.2b	85.1b	71.2b
	Wheat	Zn	42.4a	38.1c	34.1d	41.5ab	38.7bc	56.1a	27.2b	32.1b	37.7b	31.0b
		Fe	48.4	47.0	63.2	48.7	45.5	54.2	58.1	43.4	47.3	56.2
Central Butte	*Canola*	Zn	18.6b	20.8ab	24.1a	22.1ab	20.9ab	60.7ab	44.3b	54.7ab	60.7ab	70.6a
		Fe	22.8	19.9	25.9	21.5	26.0	68.7	65.0	73.6	65.1	64.1
	Pea	Zn	31.6	28.2	30.4	31.7	30.7	54.0ab	45.8b	56.4ab	69.8a	40.7b
		Fe	69.2a	43.1c	39.8bc	53.1bc	59.7ab	65.1	81.4	70.8	75.6	74.3
	Wheat	Zn	40.3a	35.2bc	35.8bc	33.9c	38.4ab	56.2a	66.5a	39.4b	46.0b	50.2ab
		Fe	39.3	29.0	30.4	28.8	33.6	54.8b	61.2ab	60.7ab	72.9a	50.0b
Rosetown	*Canola*	Zn	18.6	18.2	19.8	17.6	17.3	*NT*	*NT*	*NT*	*NT*	*NT*
		Fe	47.3	26.7	31.4	23.1	23.7	*NT*	*NT*	*NT*	*NT*	*NT*
	Pea	Zn	20.8ab	21.1ab	22.7ab	20.7b	23.8a	*NT*	*NT*	*NT*	*NT*	*NT*
		Fe	52.8bc	42.2c	37.3c	84.2ab	109.1a	*NT*	*NT*	*NT*	*NT*	*NT*
	Wheat	Zn	30.3	28.7	27.7	30.7	29.0	*NT*	*NT*	*NT*	*NT*	*NT*
		Fe	41.4	31.3	34.7	44.8	31.9	*NT*	*NT*	*NT*	*NT*	*NT*
Mawer	*Canola*	Zn	*NT*¶	*NT*	*NT*	*NT*	*NT*	38.2	31.1	38.4	42.9	41.4
		Fe	*NT*	*NT*	*NT*	*NT*	*NT*	41.9	41.8	48.3	48.6	42.2
	Pea	Zn	*NT*	*NT*	*NT*	*NT*	*NT*	36.2b	42.4ab	36.6b	42.4ab	51.7a
		Fe	*NT*	*NT*	*NT*	*NT*	*NT*	95.4ab	102.3a	83.5b	111.5a	97.7ab
	Wheat	Zn	*NT*	*NT*	*NT*	*NT*	*NT*	47.5ab	45.9ab	34.8b	43.4ab	50.0a
		Fe	*NT*	*NT*	*NT*	*NT*	*NT*	45.9ab	32.6b	53.7a	49.3a	58.0a

† Treatments labelled C, SP, F(25), F(50) and F(100) denote unfertilized control, all (100%) seed placed P, 75% applied as seed-placed and 25% applied as foliar, 50% P applied as seed-placed and 50% as foliar, and 100% P applied as foliar respectively. All fertilized treatments received a total of 20 kg P_2O_5 ha^{-1}. Means were separated using Tukey's HSD.
‡ Means for a nutrient with same letter within same crop, site and year are not significantly different (α=0.10).
§ No letters denotes no significant differences (α=0.10).
¶ NT denotes no trial was conducted at that site that year.

3.5.4.2 *Phytate*

There was no significant (P<0.10) effect of site, year, treatment or interactions on phytate concentrations measured in pea and wheat grain. Combined site and year analysis of mean phytate concentrations in the pea and wheat grain according to treatment are shown in Table 3.13. Only a significant crop effect was observed (P<0.0001), with wheat having a higher phytate content than pea. There were no significant differences or any trends apparent in the effect of P fertilization or proportion of P applied in seed-row at time of seeding versus foliar applied at mid-season on the phytate content in the grain. Comparatively, the total P uptake in wheat and pea grain are similar (Table 3.6) but phytate content of wheat is higher, indicating a greater proportion of P in wheat exists as phytate compared to pea. Previous research has observed luxury uptake of P stored as phytate and reported to be as high as 80% of P in wheat and canola seed in the form of phytate (Noack et al., 2014). Other researchers have reported a range of 50 – 80 % (Lott et al., 2002; Reddy et al., 1989) and as high as 85 % of seed P in the form of phytate (Persson et al., 2009). The pea phytate proportion of total P from this study are within this range: from 68 – 74 % while wheat had a higher range of 78 – 96 %. For both wheat and pea, the SP treatments contained the highest proportion of P in phytate form, with the control treatments wheat having the next highest proportions (73 and 89 % respectively). Similar or higher Zn concentrations in grain with increased proportion of applied P in foliar form (Table 3.12) along with relatively stable phytate content suggests that increasing the proportion of P fertilizer applied in foliar form may slightly increase the human bioavailability of the Zn in the grain due to a lower phytate: Zn molar ratio, especially since there was a trend for phytate concentration to decrease with increasing proportion of P applied in foliar form in the wheat (Table 3.13). Field sites in this study received Zn fertilizer application prior to seeding as a blanket application and this likely influenced the effect of P addition and P uptake relative to a Zn deficient soil. A decrease in ratio has also been reported to be a result of fertilization with Zn (Erdal et al., 2002). It can be difficult to establish a clear relationship between fertilizer P treatment and phytate content as in the current study when the same rate of P is applied but in different form, time and placement, though positive linear correlation between PA content and P fertilization rate in pea has been observed (Marzo et al., 1997). Higher soil P levels prior to P fertilization might account for elevated phytate in pea and wheat in this study compared to others (Barr and Ulrich, 1963; Batten et al., 1986; Chapin and Bieleski, 1982; Lee et al., 1976). High concentrations of orthophosphate in non-seed tissue has been seen to stimulate phytate production (Mitsuhashi et al., 2005), but application of P mid-season to the foliage may be less effective than P that is available and taken up early on in the growth cycle as when P is seed placed at the time of seeding. Other research, however, has found relative proportions of P species in grain were unaffected by plant P status in canola and wheat crops, with deficient, adequate, or luxury P status resulting in different concentrations of total P but the proportion of this P present as orthophosphate versus phytate varied little (Noack et al., 2014). Furthermore, the predominant P species returned to the soil in crop residue was orthophosphate followed by phytate (Noack et al., 2014). While foliar P fertilizer generally had little effect on seed phytate levels in this study, elevated P levels in straw as a result of foliar P fertilization may be returned to the soil as phytate or orthophosphate. In general, based on the results of this study it appears that foliar P fertilization may be expected to have no effect, or possibly a small positive effect on human bioavailability of micronutrient metals in pea and wheat grain. However, as the proportion of foliar P applied becomes high, a yield penalty may occur when grown under P deficient conditions.

Table 3.13: Combined analysis of 2016 and 2017 field site pea and wheat grain phytate concentrations measured using Wade's reagent phytate concentration results.

Treatment†	Pea	Wheat
	————————mg phytate g^{-1}————————	
C	10.5‡	16.1§
SP	11.1	17.7
F(25)	10.9	15.8
F(50)	9.9	14.8
F(100)	10.9	14.8

† Treatments labelled C, SP, F(25), F(50) and F(100) denote unfertilized control, all (100%) seed placed P, 75% applied as seed-placed and 25% applied as foliar, 50% P applied as seed-placed and 50% as foliar, and 100% P applied as foliar respectively. All fertilized treatments received a total of 20 kg P_2O_5 ha^{-1}.
‡ Means were separated using Tukey's HSD. Means with same letter within same crop, site, nutrient and year are not significantly different (α=0.10).
§ No letters indicate no significant difference (α=0.10).

3.5.5 Fall soil available phosphorus indices

Fertilization strategy had relatively little effect on the soil residual available P (Table 3.14). This general trend is expected as the same rate of P fertilizer (20 kg P_2O_5 ha^{-1}) was applied in all treatments but with different proportions of soil vs foliar applied. However, there were some significant differences. Phosphorus (P) fertilization generally increased the level of residual available P compared to the unfertilized control, as expected. However, the effects were not consistent among site, crop, treatment, year or method. Effects of canopy interception, retention in straw and residue along with differences in plant and microbial uptake and removal in precipitation all likely contributed to differences observed. Although some significant differences are observed among the P fertilization treatments, they are generally small and likely of limited biological significance. Where a pattern does appear, it seems that an increased proportion of the P applied in foliar form results in lower available P in the soil post-harvest. This may be explained by applied foliar P that resides in the surface thatch and residue and therefore is not included in the measurement of P in the mineral soil. The fall soil P extraction results do not suggest any disproportional mining of soil P due to foliar P treatment and are consistent with limited effects of the fertilization treatments on plant uptake observed at some of the sites. The P concentrations removed by the modified Kelowna (MK-P) were comparatively higher than the concentrations removed by water extraction, indicating water to have a lower capacity to extract soil P as revealed in previous work (e.g. Schoenau and Huang, 1991).

Table 3.14: Available P indices in soil (0-15cm) collected post- harvest from P fertilization trials in fall 2016 and 2017.

Extraction	Site	Crop	Treatment†									
			C	SP	F(25)	F(50)	F(100)	C	SP	F(25)	F(50)	F(100)
			————————2016————————					————————2017————————				
Water	Pilger	Canola	3.0‡	3.0§	3.2	2.9	3.3	4	3.7	3.9	4.2	3.8
Extractable P		Pea	2.9ab	2.4b	3.4a	2.6b	2.7ab	3.8b	4.8ab	4.2b	5.7a	4.4b
(kg P ha^{-1})		Wheat	2.8	3.2	3.1	3.1	2.8	3.4	3.8	3.2	4.1	3.7
	Central Butte	Canola	1.1	1.6	0.6	1.3	1.3	5.0b	7.4ab	6.2b	9.3a	6.0b
		Pea	1.8	1.8	2.1	2.2	2.4	4.7	5.1	5.2	4.7	4.3
		Wheat	2.2	2.2	2.2	2.5	2.3	4.3ab	5.4ab	5.0ab	6.8a	3.9b
	Rosetown	Canola	5.3	4.2	4.8	6.8	3.9	*NT*¶	*NT*	*NT*	*NT*	NT
		Pea	2.8	3.9	9.1	4.2	6.6	*NT*	*NT*	*NT*	*NT*	NT
		Wheat	7.7	7.4	8.7	6.1	5.1	*NT*	*NT*	*NT*	*NT*	NT
	Mawer	Canola	*NT*	*NT*	*NT*	*NT*	*NT*	1.7b	3.3a	2.3ab	1.5b	2.0b
		Pea	*NT*	*NT*	*NT*	*NT*	*NT*	1.7b	3.7a	2.2b	2.1b	2.1b
		Wheat	*NT*	*NT*	*NT*	*NT*	*NT*	2	2.2	2.3	2.4	1.8
MK-P(kg ha^{-1})	Pilger	Canola	15.1	15.8	15.5	14.6	14.2	9.7	8.5	7.2	11.1	9.7
		Pea	11.6b	14.4a	13.2ab	15.4a	13.2ab	8.7b	8.2b	18.8a	10.1b	9.4b
		Wheat	11.8	14.3	12.6	13.2	12.2	8.3	9.3	8.9	11.8	10.5
	Central Butte	Canola	8.7b	10.8a	9.0b	9.6ab	10.9a	13.1b	22.7a	14.7b	23.8a	17.4ab
		Pea	8.2	8.7	8.1	9.3	8	14.1	16.1	12.2	16.3	13.3
		Wheat	7.7b	9.2ab	10.3a	9.9a	9.0ab	*NT*	*NT*	*NT*	*NT*	*NT*
	Rosetown	Canola	22.4	19.8	24	29.1	20.4	*NT*	*NT*	*NT*	*NT*	*NT*
		Pea	17	21.1	29.1	19	23.6	*NT*	*NT*	*NT*	*NT*	*NT*
		Wheat	*NT*	*NT*	*NT*	*NT*	*NT*	14.4ab	16.8ab	15.1ab	19.9a	12.2b
	Mawer	Canola	*NT*	*NT*	*NT*	*NT*	*NT*	5.6	8.4	8.2	7.9	6
		Pea	*NT*	*NT*	*NT*	*NT*	*NT*	6.3b	10.9a	8.1ab	6.6b	6.2b
		Wheat	25.5	31.9	31	22.9	20.7	8.3	9.1	8.3	10.3	6.4

Membrane Exchangeable P ($\mu g\ cm^{-2}$)	Pilger	Canola	0.1a	0.1a	0.0b	0.1a	0.1ab	0.2	0.2	0.3	0.3	0.2
		Pea	0.1	0.1	0.1	0.1	0.1	0.2b	0.3b	0.5a	0.4ab	0.3b
		Wheat	0.1	0.1	0.1	0.1	0.1	0.2	0.3	0.2	0.3	0.2
	Central Butte	Canola	0.1	0.2	0.2	0.2	0.2	0.5b	0.7ab	0.6b	0.9a	0.5b
		Pea	0.1	0.1	0.1	0.1	0.1	0.4	0.6	0.4	0.5	0.4
		Wheat	0.1	0.1	0.1	0.1	0.1	0.3b	0.5ab	0.4b	0.7a	0.3b
	Rosetown	Canola	0.2	0.2	0.3	0.3	0.2	*NT*	*NT*	*NT*	*NT*	*NT*
		Pea	0.2b	0.3b	0.6a	0.3ab	0.4ab	*NT*	*NT*	*NT*	*NT*	*NT*
		Wheat	0.3	0.5	0.5	0.4	0.3	*NT*	*NT*	*NT*	*NT*	*NT*
	Mawer	Canola	*NT*	*NT*	*NT*	*NT*	*NT*	0.1b	0.3a	0.2ab	0.2ab	0.1b
		Pea	*NT*	*NT*	*NT*	*NT*	*NT*	0.1b	0.3a	0.2ab	0.1b	0.1b
		Wheat	*NT*	*NT*	*NT*	*NT*	*NT*	0.1	0.2	0.1	0.2	0.1

† Treatments labelled C, SP, F(25), F(50) and F(100) denote unfertilized control, all (100%) seed placed P, 75% applied as seed-placed and 25% applied as foliar, 50% P applied as seed-placed and 50% as foliar, and 100% P applied as foliar respectively. All fertilized treatments received a total of 20 kg P_2O_5 ha^{-1}.

‡ Means were separated using Tukey's HSD. Means for an availability assessment with same letter within same crop, site and year are not significantly different (α=0.10).

§ No letters denotes no significant differences among any treatments (α=0.10).

¶ NT denotes no trial was conducted at that site that year.

3.6 Conclusion

Under controlled environmental conditions, response to foliar P fertilization was greatest in canola, followed by wheat and pea and response diminished as proportion of P fertilizer applied in foliar form increased. Under field conditions, P application had greatest effect on increasing yield, P concentration and uptake in canola, with few significant effects in pea. The greatest response to foliar P fertilization over two years occurred at the Pilger site (Krydor association Black Chernozem), which can likely be attributed to low soil available P and better soil moisture at Pilger than the other sites. Wheat had significantly higher seed phytate content than pea, but within either crop there was no significant effect of P fertilization treatment on total phytate content. The proportion of total seed P in phytate was lower in treatments with P in foliar form versus where all P was applied in the seed-row. Observed similar or higher concentrations of Zn in grain with increased proportion of P in foliar form suggests that foliar P application may reduce phytate:Zn molar ratio and therefore slightly increase human bioavailability of Zn in grain.

4.0 Susceptibility of Foliar Versus Soil Applied Phosphorus to Export in Simulated Snowmelt Runoff and Leachate

4.1 Preface

In Chapter 3 the agronomic effects of foliar P application, including impacts on yield, uptake and seed nutrient composition were considered along with residual soil available P. This chapter focuses on the potential environmental implications of foliar versus soil P fertilizer application, in particular the dissolved reactive phosphorus (DRP) in runoff and leachate post-harvest from simulated snowmelt applied to soils that had received different proportions of foliar versus soil applied P fertilizer.

4.2 Abstract

As crop yield potential increases, addressing soil P deficiency through fertilization can become more challenging, as more P fertilizer will be needed to balance off higher crop removal. However, when P applied exceeds crop removal, P levels in soil can build up that are susceptible to export off-site with water from rain and snowmelt events that can subsequently enter into surrounding waterbodies. While soil applications of P fertilizer have received attention for their impact on P export in run-off, few studies have evaluated foliar application of P as a fertilization strategy for reducing P in runoff. A study was conducted to evaluate foliar P application compared to soil application for its influence on potential P export in snowmelt runoff-leachate. Sites in the Brown (Central Butte) and Black (Pilger) soil zones of Saskatchewan were used for controlled environment and field studies in which wheat, pea and canola received varying proportions of mid-season applied foliar P fertilizer versus soil applied P at seeding. After harvest, intact soil blocks from the pea, wheat and canola controlled environment studies and intact soil slabs collected from wheat plots in the field study at Central Butte location were used for a simulated snowmelt runoff-leachate study to evaluate the effect of foliar P application on DRP content in snowmelt runoff/ leachate. The P treatments evaluated were a control with no added P, 20 kg P_2O_5 ha^{-1} that was applied all with the seed, all foliar applied, and split between foliar and soil application. Application of P in foliar form versus seed-placed, or a combination thereof, did not have a consistent positive or negative effect on P export in snowmelt runoff-leachate, with the effects dependent on crop and soil type. While P fertilizer application in general tended to increase DRP concentrations, high crop interception and uptake, such as by canola, was associated with overall reduced P loss in snowmelt run-off and leachate compared to pea and wheat. No P treatments exceeded the environmental thresholds for Canadian prairie water bodies set by Glozier et al., (2006) of 0.26 mg P L^{-1}. The DRP concentration in simulated snowmelt runoff-leachate from the controlled environment study in which wheat, pea and canola was grown ranged from 0.019 – 0.11, 0.022 – 0.084 and 0.004 – 0.043 mg P L^{-1} respectively. In the slabs of soil taken from the wheat plots in the field at the Central Butte site, the DRP ranged from 0.100 – 0.124 mg P L^{-1}, with the highest concentration found in the treatment in which all P was seed-placed. With the exception of wheat grown on the Pilger soil under controlled environment conditions, P fertilization in which some or all MAP was applied in the seed-row resulted in higher concentrations of DRP in the snowmelt runoff-leachate than foliar application.

4.3 Introduction

The major environmental concern surrounding P fertilizer application to farm fields is its potential contribution to non-point source pollution of water bodies on the Canadian Prairies (Li et al., 2011; Miller et al., 2004). As well, there is an economic loss to the producer associated with the export of P derived from fertilizer in water runoff (Alberts et al., 1978). Soils in northern regions such as the Canadian Prairies undergo extended annual periods of freezing temperatures with continuous snow cover for 4-5 months (Cade-Menun et al., 2013). The spring snowmelt can account for upwards of 80 % of total annual surface runoff on the prairies (Dunne 1983; Shrestha et al., 2011). Phosphorus (P) loading impairs water quality and has been attributed to eutrophied water bodies such as Lake Winnipeg (Lake Winnipeg Stewardship Board, 2006) and Lake Erie (Michalak et al., 2013).

Strategies have been identified to reduce the contribution of agricultural soils to P loading in water, such as in-soil fertilizer P placement to reduce dissolved inorganic P losses compared to surface broadcasting (Weiseth, 2015; Wiens, 2017), and conservation tillage to reduce particulate P losses in water erosion (Kleinman, 2009). Export of P into surface waters primarily occurs through surface runoff and subsurface flow (King et al., 2015) in either dissolved or particulate form (Correll, 1998). Management practices such as conservation tillage significantly reduce nutrient loss in particulate form, however due to lack of soil inversion nutrients may be stratified at the soil surface, increasing nutrient loss in dissolved form (Cade-Menun et al. 2010; Ginting et al. 1998; Hansen et al. 2000; Li et al. 2011; Tiessen et al. 2010;). Frozen soil limits particulate detachment (Panuska et al., 2008) which also results in greater proportions P in dissolved form than particulate (Cade-Menun, 2013), especially on the Canadian prairies. Limited infiltration rates in frozen soil enables further transport of nutrients from fertilizers at the surface, and from non-desiccated plant material (Tiessen et al. 2010; Timmons et al. 1970; Young and Mutchler 1976). Furthermore, high rates of applied P as manure and fertilizer which exceed crop uptake and are applied to the soil surface such as broadcast inorganic fertilizer and manure that goes unincorporated can increase P export in surface runoff (Weiseth, 2015; Wiens, 2017 King et al., 2017).

As crop yield potential increases, addressing soil P deficiency through fertilization can become more challenging, as more P fertilizer is needed to balance off higher crop removal. However, the amount of P fertilizer that can safely be placed in soil near the seed is limited and placement cannot be too far away from the roots due to the low mobility of P in the soil. As noted previously, broadcast application to the soil surface without incorporation results not only in reduced efficiency of uptake but also potentially increased export in run-off. Foliar application of P is another fertilizer P application strategy that has received little attention for its potential impacts on P export in runoff and leaching water. Research evaluating the impact of commercial inorganic P fertilizers, particularly foliar P, on water P export in prairie soils is limited. The chapter aims to address this gap.

The objective of this research was to evaluate how 20 kg P_2O_5 ha^{-1} that is applied as mono-ammonium phosphate in the seed-row at seeding versus all applied as K_2PO_4 fertilizer dissolved in water to wheat, pea and canola foliage at canopy closure, and different proportions of seed-placed versus foliar applied P, influences the following:

1) The concentration of DRP in simulated snowmelt water from snow applied to intact soil blocks taken post-harvest from a growth chamber tray study in which canola, pea and wheat were grown on a Brown (Central Butte site) and Black (Pilger site) Chernozem under different foliar versus soil P application treatments.
2) The concentration of DRP in simulated snowmelt water using frozen intact surface soil slabs collected after harvest in the fall of 2017 from the Central Butte site field P treatment wheat plots.

4.4 Materials and Methods

4.4.1 Snowmelt simulation and P analysis

4.4.1.1 *Controlled environment tray study*

To measure how foliar treatments potentially influence P export in snowmelt runoff-leachate water, a simulated snowmelt study was conducted on soil blocks removed from the trays that were used in the controlled environment study described in detail in chapter 3, after crop harvest from the trays. The soil blocks were 12.5 cm width, 35 cm length and 10 cm deep. The soil was removed from the trays as intact blocks after the crops were harvested that were then air-dried and placed inside insulated wooden boxes lined with plastic to funnel the leachate water into plastic buckets (Figs. 4.1, 4.2). Then addition was made of 2.0 kg (~15-cm) of snow placed on top of the soil in the boxes and the soil slab + snow allowed to melt at 20 ^{o}C for 24 hours. This provided a simulation of potential for P movement in snowmelt run-off/leachate from a late fall snowfall event. Snow for the study was collected immediately after a snowfall event close to Waldheim, SK at N 50° 08.047’ W 104° 36.554’. As the boxes were tilted at an 8^{o} angle, as snowmelt occurred, the snowmelt runoff was collected over the 24 hours and the volume measured at the end. The collected run-off was filtered through a 0.45 micron filter paper to determine the DRP concentration following the method of Smith et al (2011) and King et al (2017), and analyzed for DRP colorimetrically using an automated colorimetry system (Technicon AA2 continuous flow system) based on ammonium molybdate reaction with P (Murphy and Riley 1962). The snow itself was analyzed for background P concentration and this was subtracted from the P measured in the runoff water from the slabs.

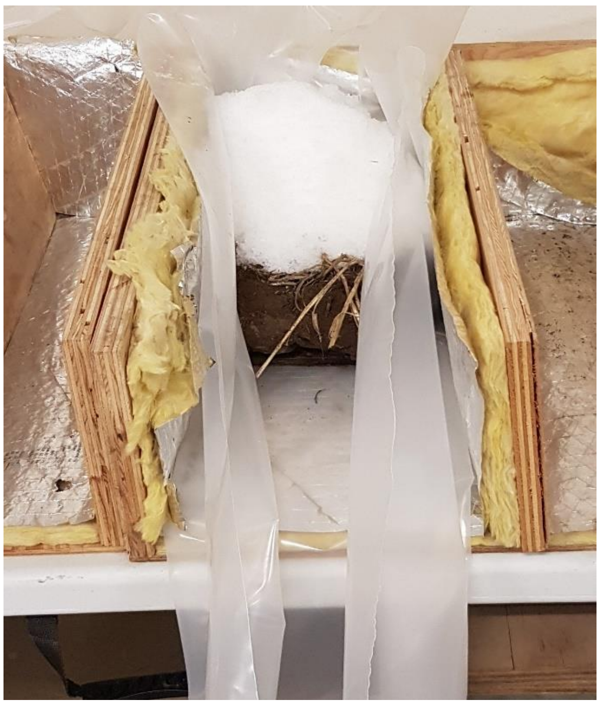

Figure 4.1: Frozen soil slab inside insulated box with melting snow on the soil surface to create snowmelt leachate.

Figure 4.2: Snowmelt passing through soil slabs with plastic funneling the runoff and leachate water into collection containers.

4.4.1.2 *Field plot study*

This study followed the procedure used and described by King et al. (2017) in which intact surface slabs of soil were collected from the field trial wheat P treatment replicate plots at the Central Butte field site in October of 2017. In this method, a trench was dug in a square in the center of the field plot to enable an intact slab of soil to be removed at the base by sliding acrylic glass (poly (methyl methacrylate)) underneath and carefully removing from the pit (Fig. 4.3).

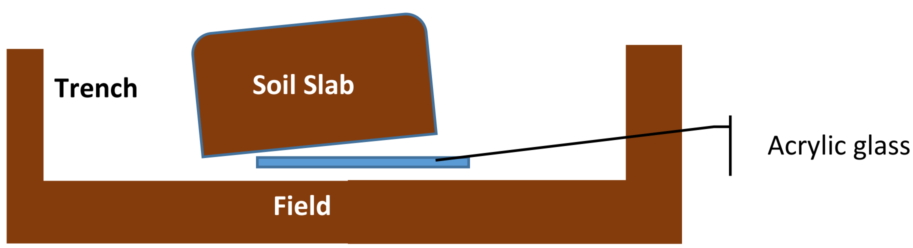

Figure 4.3: Illustration of soil slab collection from Central Butte field site.

The intact slabs were carefully packaged for transport using plastic wrap, and brought to Saskatoon where they were immediately frozen at -20 ^{o}C to simulate winter freezing. Slab size was approximately 25 cm length by 20 cm width x 10 cm deep. Exact dimensions for each slab were recorded. Frozen slabs were placed in insulated boxes lined with plastic tilted at 8^{o} slope that funneled the runoff/ leachate water into plastic buckets (Fig. 4.5). The melt was conducted at 12 ^{o}C with 1 kg (~7.5-cm) of snow added every 24 h over a 48 hour period, with collected runoff frozen between collection periods to avoid P transformations via microbial activity in the collected water. The DRP was measured in the snowmelt run-off/leachate water collected as described in section 4.4.1.1 for the controlled environment tray study. The snow was analyzed for background P concentrations and this was subtracted from the P measured in the runoff-leachate water collected from the slabs.

4.4.2 Statistical data analysis

Where applicable, means separations were performed using PROC GLIMMIX in SAS (version 9.4; SAS Institute, Cary, NC). Tukey's protected HSD was used for multi-treatment comparisons with an alpha level of 0.10. Treatment and crop were analysed as fixed effects with block analysed as a random effect. Outliers were determined by Grubbs Test.

4.5 Results and Discussion

4.5.1 Foliar P controlled environment trial

The *P* values from the snowmelt runoff-leachate collected from controlled environment studies (Table 4.1) indicate no significant crop, P treatment or crop by treatment effect in the Central Butte soil, but do show significant effects for all three factors in the Pilger soil. This continues the trend of the low soil available P Pilger site as being generally the most responsive site to treatment in this study. These findings agree with the results of Weiseth (2015) and Wiens (2018). In their comparisons of MAP fertilizer placement on P removed in snowmelt runoff-leachate, only the low P fertility soil used by Weiseth (2015) showed a significant effect of MAP placement method on export in simulated snowmelt. In the current study, the crops that showed significant responses to soil versus foliar P fertilization treatment were wheat and pea while canola (P = 0.1203) did not.

Table 4.1: *P* values for treatment effect on dissolved reactive phosphorus (DRP) concentrations in simulated snowmelt runoff and leachate using Tukey's protected HSD for fixed effects in soil versus foliar P applied P controlled environment studies using Central Butte and Pilger site soil.

Site Soil	Effect	Numerator df	P Runoff-Leachate
Central Butte	Crop	2	0.2533
	Treatment	3	0.1146
	Crop*Treatment	6	0.5322
Pilger	Crop	2	**0.0002**
	Treatment	3	**0.0079**
	Crop*Treatment	6	**<.0001**

Bolded values are significant at P<0.10.

The DRP concentrations in the post- harvest controlled environment run-off - leachate from the Central Butte site soil (Fig. 4.4) ranged from 0.004 mg P L^{-1} to 0.084 mg P L^{-1}. The greatest DRP levels were measured in the wheat F(50) treatment, which was significantly greater than the C and F(100) treatments. No significant differences were observed among foliar P treatments in pea or canola, although concentrations of P in runoff-leachate from the soil on which pea was grown was generally higher. This may reflect higher content of soluble P in remaing pea straw and roots after harvest compared to the other two crops.

The snowmelt DRP concentrations from the Pilger soil (Fig. 4.5) were of a slightly wider range, from 0.002 mg P L^{-1} to 0.11 mg P L^{-1}, compared to the Central Butte soil. The greatest DRP concentration in the post-harvest snowmelt runoff and leachate was found in the Pilger soil wheat F(100) treatment which was signficantly greater than all other wheat treatments. This follows a trend similar to that observed in the Central Butte soil, where P concentrations in snowmelt overall tended to be higher in wheat and pea stubble than in canola. This may be a consequence of greater P uptake by the canola, leaving less P behind in the soil, roots and surface residue. Differences in leaf architecture may also contribute to differences observed, with the broader, flatter orientation of the canola leaves resulting in greater interception of the foliar P spray (Fernandez et al., 2013). The SP treatment had the highest DRP concentrations in the run-off and leachate from the trays with peas, which was significantly greater than all other treatments, while F(50) treatment was significantly higher than the C and F(100) treatments in canola. In both sites, the greatest DRP levels were measured in wheat while the lowest were in canola.

Overall, application of P fertilizer tended to increase DRP concentration in runoff and leachate collected which is consistent with other studies showing that soils that received P application had increased concentrations in runoff, particularly when P rates exceeded crop uptake (Cade-Menun et al., 2013; King et al., 2017; Weiseth, 2015; Wiens, 2017). However, in this study there appears to be no consistent effect relating to proportion of P that was applied in the seed-row versus foliar applied among all crops and sites. In the Central Butte soil, the F(100) treatment had the lowest DRP for all three crops and the effect was significant for wheat, while at Pilger site, wheat had the highest DRP in the F(100) treatment. The results for the Pilger wheat suggest that high rates of foliar P on wheat would cause more P runoff, especially compared to canola with greater foliar P interception by leaves and also greater uptake. Canola yields in Pilger soil were considerably higher than pea or wheat (see Chapter 3), with greater overall nutrient uptake that likely contributed to less P in the runoff-leachate from the soil on which canola was grown. However in the Central Butte soil, DRP concentrations tended to closely follow the proportion of P that was seed placed MAP, and there was less difference among crop yields to create large differences in P uptake. It is concluded that neither seed-row placed or foliar applied P method of application produces consistently lower DRP concentrations in run-off and leachate. As the results of this study show, the effect of altering proportion of soil applied versus foliar appears dependent on crop and soil type.

It is important to note that in this study, a portion of P applied was likely to have remained unmeasured in the root material and in the stalks at the base where the plant was cut during harvest. Noack et al. (2012) found orthosphosphate to be the most prevalent form of P in wheat, canola and pea chaff, and soluble P in remaining roots, stalks and litter would contribute to P export. Furthermore Martin and Cunningham (1973) found rapid release of 85 % of the total P contained in dried wheat roots, in which greater than 90 % existed as orthophosphate. Orthosphosphate is generally the most prevalent form of soluble P in water extractions of soil (Noack et al., 2012), and nutrients in snowmelt runoff are mainly in the dissolved form rather than particulate (Cade – Menun et al., 2013; Hansen et al., 2000; Tiessen et al., 2010). In a spring snowmelt water runoff scenario, P is lost from residual soil fertilizers and also via leaching of soluble inorganic and organic P that is derived from soil organic matter or plant residues, with DRP desorbed from the surface of colloids the water is passing through and also from soil particles suspended in the snowmelt (Ulen, 2003). The water extractable P method used for this study has been found to be significantly correlated with P in leachate (Wang et al., 2012; Wang et al., 2010; Wiens, 2017; Penn et al., 2006; Turner et al., 2004). Water extractable soil P concentrations measured in the fall in the Central Butte site field study (see Chapter 3) display a trend in which the post-harvest water extractable P levels in the wheat plots were consistently higher than canola, which could be attributed to the observed higher P uptake and removal by the canola. A similar trend was observed in the Central Butte soil controlled environment study, in which the greatest DRP concentrations were measured in the wheat and generally the lowest in the canola. Wheat in the Central Butte soil appeared to show greater risk of snowmelt runoff P losses with higher rates of seed placed MAP than canola. While the greatest range of P leachate was measured in the Pilger soil, the Central Butte soil generally had higher DRP concentrations in treatments receiving seed placed MAP, which is consistent with lower P fixation that might be expected in the Central Butte soil with its lower clay and organic matter content compared to the Pilger soil.

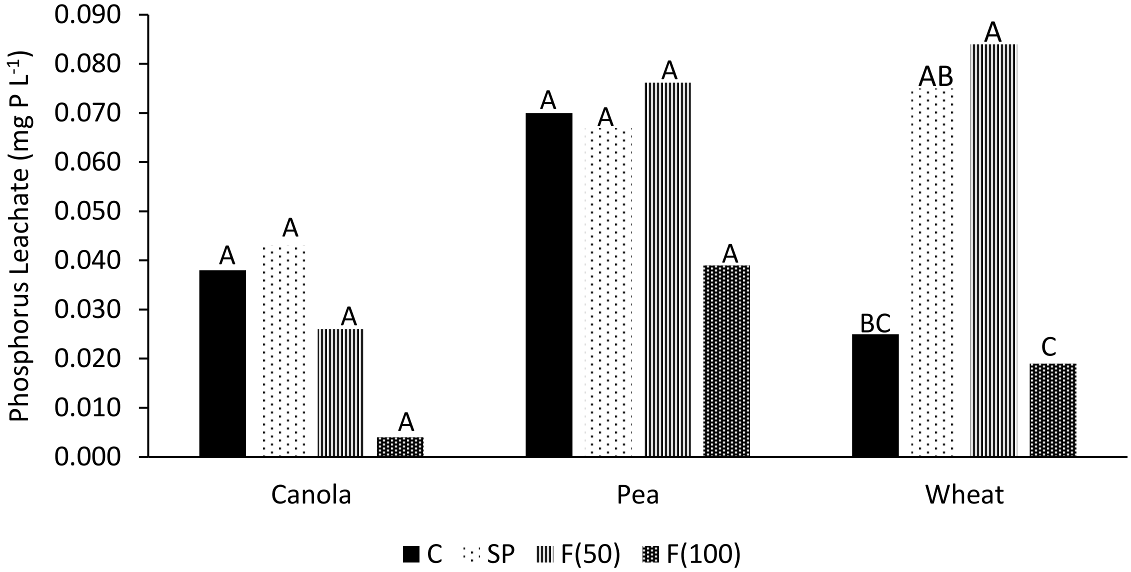

Figure 4.4: Simulated snowmelt runoff - leachate dissolved reactive phosphorus (DRP) concentrations (mg P L^{-1}) from Central Butte site soil in controlled environment study. Treatments labelled C, SP, F(50), F(100) denote unfertilized control, all P (100%) seed placed, 50% P applied as foliar and 50% as seed placed, and 100% P applied as foliar respectively, at a rate of 20 kg P_2O_5 ha^{-1}. Total leached P means were separated using Tukey's HSD. Means with same letter within a crop are not significantly different (α=0.10).

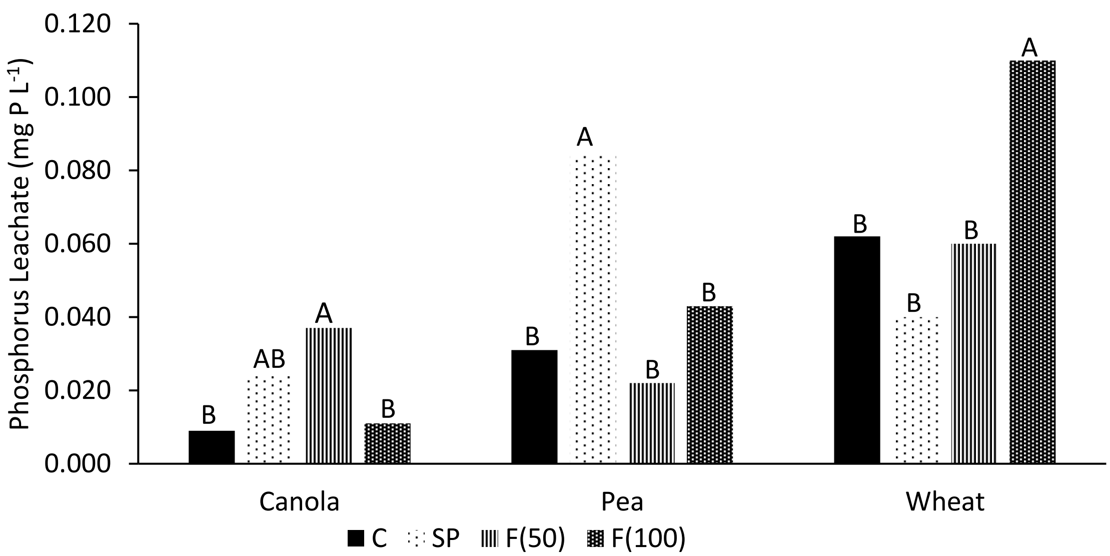

Figure 4.5: Simulated snowmelt runoff - leachate dissolved reactive phosphorus (DRP) concentrations (mg P L^{-1}) from Pilger site soil in controlled environment study. Treatments labelled C, SP, F(50), F(100) denote unfertilized control, all (100%) P seed placed, 50% P applied as foliar and 50% as seed-placed, and 100% P applied as foliar respectively, at a rate of 20 kg P_2O_5 ha^{-1}. Total leached P means were

separated using Tukey's HSD. Means with same letter within a crop are not significantly different (α=0.10).

4.5.2 Foliar P field trial

The simulated snowmelt runoff and leachate study conducted on intact soil slabs removed post-harvest from the 2017 Central Butte site field trial wheat plots (Fig. 4.6) revealed comparatively higher DRP runoff- leachate concentrations than measured in the controlled environment growth chamber tray study. In the slabs collected from the field trial, DRP concentrations ranged from 0.100 to 0.190 mg P L^{-1}. This may be explained by greater interaction of the snowmelt water with the soil and surface residue in the intact slabs compared to the tray study where surface soil was excavated from the field, mixed and fresh crop residue removed prior to placement in the trays. The concentrations of DRP in the slabs collected from the field study are therefore likely to more closely approximate what would be observed in the field. In the field slabs, the treatment where all of the 20 kg P_2O_5 ha^{-1} was placed in the soil in the seed row (SP) had significantly higher DRP concentration than the control or treatments where a portion of the P was foliar applied. In the Central Butte controlled environment study, the seed-placed and 50% seed-placed-50% foliar treatments had the highest DRP concentrations (Fig. 4.4). This could reflect more of the foliar applied P being immobilized in surface soil residue through conversion to organic forms that do not form part of the DRP that is measured in the runoff-leachate water. Foliar P application had no effect on snowmelt DRP concentrations compared to the unfertilized control (Fig. 4.6). Overall elevated DRP levels observed in the field study may also be the result of the wet-dry and freezing and thawing processes that the field soil slabs underwent compared to only the wetting and drying of the controlled environment slabs. Freeze-thaw cycles have been linked to greater release of nutrients from plant material (Bechmann et al., 2005). Furthermore, in frozen soil interaction is mainly between snowmelt and the soil surface but as the soil thaws, greater interaction has been noted between water and the soil at depth (Wiens, 2017). Due to the greater volume of soil and plant material in the slabs taken from the field site it is possible there was a greater DRP contribution from P fractions in the field slabs compared to the controlled environment tray blocks.

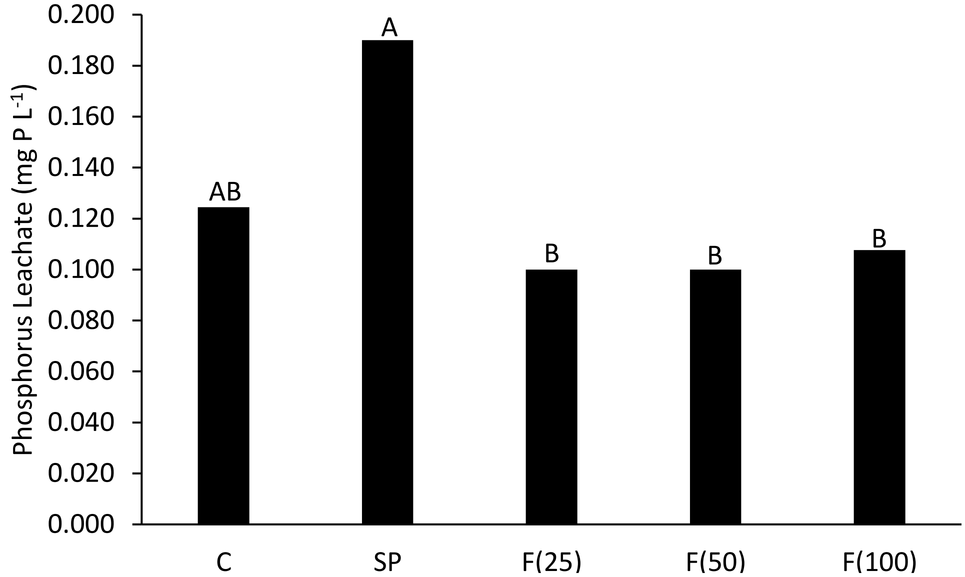

Figure 4.6: Simulated snowmelt runoff and leachate dissolved reactive phosphorus (DRP) concentrations (mg P L^{-1}) from Central Butte site field study soil slabs collected post- harvest from wheat plots in October 2017. Treatments labelled C, SP, F(25), F(50), F(100) denote unfertilized control, all (100%) P seed-placed, 25% P applied as foliar and 75% seed placed, 50% P applied as foliar and 50% as seed placed, and 100% P applied as foliar respectively, at a rate of 20 kg P_2O_5 ha^{-1}. Total leached P means were separated using Tukey's HSD. Treatment was not statistically significant (*P*= 0.2018). Means with same letter within a crop are not significantly different (α=0.10).

All DRP snowmelt-leachate values obtained from both field and controlled environment studies were generally lower than the range reported by Cade-Menun et al., (2013) for cropland P runoff (0.1 – 0.6 mg P L^{-1}). All leachate values observed in this study were below the threshold concentration for total P for a healthy water body on the Canadian Prairies reported to be 0.26 mg P L^{-1} (Glozier et al., 2006). Overall under the parameters set in this study, application of P in foliar form versus seed-placed, or a combination thereof, did not have a consistent positive or negative effect on P export in snowmelt runoff and leaching that was independent of crop or soil type. With the exception of wheat grown on the Pilger soil under controlled environment conditions, P fertilization in which some or all MAP was applied in the seed-row resulted in higher concentrations of DRP in the snowmelt runoff-leachate than foliar application. While P fertilizer application in general tended to increase DRP concentrations, high crop interception and uptake appears to be associated with reduced P loss in snowmelt run-off and leachate. Effect of runoff passing specifically through loose chaff and senesced leaf material was not evaluated in the controlled environment studies, which may be more significant contributors to P leaching.

4.6 Conclusion

Overall, effects on potential P export in snowmelt were somewhat variable. In the Central Butte wheat stubble soils under field conditions, the treatment with all P placed in seed-row at time of seeding had highest P concentration in run-off. In controlled environment study soils, P fertilization in which some or all MAP was applied in the seed-row tended to result in higher concentrations of DRP in the snowmelt runoff-leachate compared to foliar application. However this was not consistent across all sites and crops. In Pilger site wheat, the high rate foliar had highest concentration of dissolved reactive P in run-off. Overall, effects on potential P export in snowmelt that were observed in this study were somewhat variable and require further investigation, such as the potential of P fertilizer stratified at the soil surface to contribute to subsequent soil P pools.

5.0 SYNTHESIS AND CONCLUSION

Of the crops evaluated in this study, canola was the most responsive to foliar P fertilization with pea the least. Increased mid-season P tissue concentrations and P uptake observed after foliar treatment in the absence of seed placed MAP indicates that some uptake of foliar P occurred in canola. While uptake did occur, it was not associated with consistent, significant positive yield and P uptake responses at harvest. In this study, soil P arising from pre-existing pools and/or from MAP fertilizer addition at seeding, was a greater contributor to plant growth than foliar applied P, as response per increment of foliar P was less than for MAP addition. Significantly higher wheat grain and biomass yields have been reported in previous research with foliar application in addition to recommended rates of soil applied P fertilizer (Samad et al., 2014), and low rates of foliar P (~2 kg P ha^{-1}) have been stated to increase P use efficiency (Mosali et al., 2006). Foliar P is most effectively absorbed by plants when intercepting leaf area is high, and this may explain the greater responsiveness of canola observed in the current study. As well, cereal crops such as wheat require P early in the season (sowing) to promote root growth and tillering and are noted to be particularly responsive to starter seed placed P (Noack et al., 2010). Canola and wheat have been measured to have similar leaf area indexes (LAI) peaking at about 6 m^2 of leaf surface area per m^2 of ground surface (Tripathi et al., 2018) with pea peaking around 1 m^2m^2 (Beasse et al., 2000). Crop stage is likely to have been a factor in the current study as P demand prior to anthesis when the foliar application was made may have been less than at anthesis. Timing of application should coordinate with plant nutritional status in which a plant is deficient for only P. The Feekes 7 growth stage has been suggested to be the optimum stage for foliar P application to cereals as it coincides with the stage in which N is also often foliar applied (Mosali et al., 2006). Sequential applications of equal, low rates of foliar P at tillering, boot and anthesis to supplement seed placed P has been recommended (Samad et al., 2014) and may be considered for future testing on the prairies, but is likely to be uneconomical. It is important to consider that the increased P use efficiency associated with multiple foliar P applications may not outweigh the crop trampling, fuel, equipment and labor costs associated with more field operations as well as the opportunity cost in which another management strategy would be more appropriate i.e. N or N + P foliar application (Noack et al., 2010). Part of maximizing foliar P efficiency is combining P application with another management practice such as a herbicide or fungicide application as these can coincide with periods of high plant P demand. In addition, there appears to be no ideal or suggested formulation which combines the appropriate form of P with the most effective adjuvant, however acidic P solutions have been suggested to be more effective than neutral or alkaline solutions (Noack, 2010). The challenges associated with maximizing response to foliar

P application while maintaining optimal efficiency has been a challenge for improving the effectiveness of foliar P relative to seed placed P (Boynton, 1953; Noack et al., 2010).

Increased grain yield associated with P fertilization has been observed to come at the expense of reduced Zn concentration and bioavailability (Zhang et al., 2012). While some antagonistic effect was observed between Zn and seed-placed P fertilizer in the current study, foliar P fertilization appeared to have no notable effect on Zn uptake as well as the anti-nutritional phytate content. Factors such as crop stage or climatic conditions may have inhibited foliar P uptake, reducing its effect on Zn uptake and phytate production. Applying Zn as a foliar spray has been recommended to counteract the inhibited Zn uptake caused by P fertilization (Zhang et al., 2012). Other research has found combinations of Zn and P fertilizers to have less impact on yield and Zn content than Zn alone or Zn + N or K (Wang et al., 2017). It could be expected that under conditions where significant response to foliar P fertilization is observed, notable shifts in nutritional content might occur and should continue to be explored in future research with foliar P fertilization. While high concentrations of orthophosphate have been reported to increase plant phytate (Mitsuhashi et al, 2005), the limited rate of foliar P which can effectively be applied to increase plant P nutrition is likely to have limited effect on plant phytate production, as foliar application does not appear to influence tissue P content much differently than seed placed P fertilizer.

Due to the inherent immobility of P in soil, leaf uptake was most likely to have occurred as opposed to foliar P reaching the soil surface and moving to plant roots, if not stratified at the soil surface. Stratified P could pose a risk of being exported in leachate or runoff but this study found no evidence of this occurring at the applied rates (20 kg P_2O_5 ha^{-1}) used. Considering the reactivity of P with the soil and the high P fixing potential of some of the calcareous soils used in this study, foliar P that runs off the foliage and is stratified at the surface in mineral soil from rates as high as 20 kg P_2O_5 ha^{-1} may be less prone to export in run off than P that is taken up and subsequently resides in straw residues (Mcbeath et al., 2011; Rose et al., 2013). While foliar P fertilization at the applied rates had little impact on soil P snowmelt runoff/leachate concentrations, the leaching potential of foliar P fertilizer contained within or adhering to crop residue left behind after harvest was not directly evaluated in this study. However, foliar P fertilization did little to influence straw P content, leaving little to suggest that adsorbed P, as a result of foliar P fertilization, would increase the potential for P leachate from straw residue. Any P export from straw tissue is unlikely to be significant as the vast majority of P in crops such as wheat and pea resides in the grain, with only a small proportion in the straw (Batten et al., 1986; McBeath et al., 2011). Greater export of P in water leachate is generally associated with soils high in P

(Svanback et al., 2015), however foliar P fertilization is most suitable in P deficient soils. Previous research on P runoff in Saskatchewan found rates as high as 80 kg P_2O_5 ha^{-1} as granular MAP broadcasted on the soil surface resulted in luxury uptake and increased crop P removal as well as greater export of DRP in runoff and leachate compared to lower rates of 20 kg ha^{-1} (Wiens, 2017). As the fertilizer rates applied in the current study did not exceed 20 kg P_2O_5 ha^{-1}, foliar P application can be expected to have minimal effect on P export in water at the rates in this study. Foliar P fertilizer rates high enough to achieve notable P export levels would be far higher than the necessary amount to achieve maximum foliar uptake. It is important to consider subsequent effects of foliar fertilization that weren't analyzed in this study. There was a trend for increased proportion of P applied in foliar form to result in reduced residual concentrations of labile P in the top 15cm of soil after harvest that might be attributed to P that is immobilized in organic form in the surface thatch, as noted by Wiens (2015) for broadcast P. Even under low uptake conditions, foliar P fertilizer could potentially contribute to future soil P fertility, in which case foliar P applied during the same time as a herbicide or fungicide application is both available for plant uptake (as needed) with the rest -depending on management practices- returned to the soil.

Maximizing uptake efficiency of foliar P fertilizer and indeed showing response to foliar P fertilization can be difficult, as demonstrated in the results of this study. It appears to require the simultaneous combination of rather severe soil P deficiency, high crop P demand, and growth promoting environmental conditions. This is further complicated by the limited quantity of P that is able to be absorbed by leaves as well a limited window of leaf uptake activity and the influence of environmental conditions like moisture stress, limiting the rate of foliar P which can be effectively applied. In soils with relatively good inherent P fertility that have been managed well, such as the Rosetown site Sutherland association soil, reducing or omitting P fertilizer may be the best management practice both financially and environmentally as a means to reduce excess soil P (Wiens, 2017). This study only evaluated KH_2PO_4 as a foliar P source. There are others like ammonium polyphosphate and humic-phosphate products available to growers that also should be studies. More research is needed to evaluate the potential of different foliar P fertilizer compounds along with different adjuvants, as well as fertilizer blends in addition to evaluating application timing among different crops before blanket recommendations can be made. In this study, foliar KH_2PO_4 fertilization was a poor substitute for seed-placed MAP, which could a result in an absence of early season crop 'pop-up' effect, otherwise seen with seed-placed P fertilizers in small grains production on the prairies. Considering the degree of uptake that is able to occur, there is greater potential for foliar P as a top-up or supplemental fertilizer treatment to go along with seed-placed P as opposed to a substitute. The challenge is balancing crop P demand and timely application of foliar P to maximise both uptake and efficiency. Foliar P fertilization may be relatively ineffective for oilseeds, cereals and pulses in dryland agriculture compared to vegetable, nut or fruit crops grown under irrigation (Noack et al., 2010). The results of this study suggest overall uptake of foliar P fertilizer by plant leaves wasn't high enough to make a notable impact on the parameters evaluated in this study on an annual basis. These results underline the importance of the right source, time, placement and rate regarding P fertilization of canola, wheat and pea in contrasting Saskatchewan soils.

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7.0 Appendix A

Table A.1: Spring pre-seed soil characterization for pH, EC, and MK-extractable P at 15-30 and 30-60cm soil depths at the field trial sites.

Year	Site	Association	Depth (cm)	Extractable P (kg ha^{-1})†	pH	EC	%OC
2016	Pilger	Krydor	15-30	17	7.9	2.7	3.8
			30-60	.	.	.	.
	Central Butte	Echo	15-30	13	8.0	0.2	0.9
			30-60	.	.	.	.
	Rosetown	Sutherland	15-30	16	8.2	0.2	1.6
			30-60	.	.	.	.
	St Brieux	Flooded out 2016	15-30	9	8.1	0.2	1.1
			30-60	.	.	.	.
2017	Central Butte	Echo	15-30	25	8.2	0.2	1.5
			30-60	20	8.3	0.2	1.2
	Pilger	Krydor	15-30	36	8.4	0.3	2.4
			30-60	59	8.4	0.3	2.4
	Mawer	Weyburn	15-30	16	8.1	0.2	0.9
			30-60	23	8.2	0.2	1.0

† Extractable P was measured using modified Kelowna (MK) method.

Table A.2: 2016 spring pre-seed soil characterization for membrane exchangeable P.

Site	Depth (cm)	µg cm^{-2}
Pilger	0-15	0.03
	15-30	0.00
Central Butte	0-15	0.19
	15-30	0.12
Rosetown	0-15	0.60
	15-30	0.03
St. Brieux	0-15	0.37
	15-30	0.06

Table A.3: Spring pre-seed soil characterization for available NO_3, SO_4 and K at multiple soil depths at foliar P trial sites.

Year	Site	Depth (cm)	Nutrient		
			NO_3	SO_4	K

			————kg ha^{-1}————		
2016	Pilger	0-15	24	538	379
		15-30	10	947	1262
		30-60	7	1040	.
	Central Butte	0-15	7	15	293
		15-30	7	9	919
		30-60	5	14	.
	Rosetown	0-15	12	9	204
		15-30	10	8	935
		30-60	7	24	.
	St. Brieux	0-15	18	16	192
		15-30	12	13	841
		30-60	10	9	.
2017	Pilger	0-15	24	24	807
		15-30	23	39	740
		30-60	14	63	524
	Central Butte	0-15	19	9	711
		15-30	20	16	890
		30-60	14	16	660
	Mawer	0-15	9	6	348
		15-30	11	10	572
		30-60	8	11	453

8.0 Appendix B

Table B.1: Foliar P 2016 and 2017 field trial P values for crop, treatment and crop* treatment effect for grain and straw N across all sites.

Year	Site	Effect	Straw N	Grain N
2016	Pilger	Crop	**<.0001**	**<.0001**
		Treatment	0.9300	**0.0016**
		Crop*Treatment	0.4590	**0.0004**
	Central Butte	Crop	**<.0001**	**<.0001**
		Treatment	0.9349	0.8393
		Crop*Treatment	**0.0160**	0.1473
	Rosetown	Crop	**<.0001**	**<.0001**
		Treatment	0.9254	0.9649
		Crop*Treatment	0.4190	0.8146
2017	Pilger	Crop	**<.0001**	**<.0001**
		Treatment	0.6386	0.2535
		Crop*Treatment	0.6886	0.2653
	Central Butte	Crop	**<.0001**	**<.0001**
		Treatment	0.3092	0.9949
		Crop*Treatment	0.2369	0.3886
	Mawer	Crop	**<.0001**	**<.0001**
		Treatment	0.1498	0.5594
		Crop*Treatment	**0.0050**	0.5628

Bolded values are significant at $P<0.10$.

Table B.2: 2016 and 2017 field trial canola, pea and wheat grain and straw harvest samples measured for N uptake.

Year	Site	Crop	Straw N					Grain N				
			C†	SP	F(25)	F(50)	F(100)	C	SP	F(25)	F(50)	F(100)
			——————————————————————kg ha-1——————————————————————									
2016	Pilger	Canola	11.6b‡	17.1a	9.6b	10.5b	12.2ab	38.8c	134.4a	57.5bc	61.2bc	63.3b
		Pea	20.5§	17.0	19.6	17.6	18.3	89.1	84.6	90.5	96.9	78.3
		Wheat	11.2	10.3	11.6	11.5	11.0	38.4	49.1	42.6	46.8	37.6
	Central Butte	Canola	8.5	7.3	6.7	7.8	9.9	108.3a	83.2ab	70.2b	89.8ab	108.5a
		Pea	22.4a	15.8b	20.1a	20.0a	20.0a	145.1	121.7	131.2	129.1	140.6
		Wheat	6.7b	11.1a	8.5ab	8.3ab	7.3b	72.6b	107.2a	90.7ab	100.5a	74.8b
	Rosetown	Canola	9.1	7.1	8.6	8.7	10.6	113.9	94.0	108.0	102.8	124.7
		Pea	17.9	20.0	16.7	20.2	17.9	125.9	136.4	109.6	129.7	118.8
		Wheat	14.8	13.1	11.9	12.1	11.9	73.9	79.1	71.7	69.8	70.0
	St. Brieux	Wheat	12.7	15.7	11.1	12.2	15.0	56.4	56.7	39.0	49.4	54.3
2017	Pilger	Canola	14.8	19.2	16.8	17.4	19.1	90.0b	117.1a	120.9a	105.5ab	104.3ab
		Pea	28.4ab	29.8ab	36.3a	24.0b	28.4ab	78.0b	103.4a	76.9b	67.7b	87.1ab
		Wheat	4.1	3.1	2.4	1.7	3.4	24.7	20.4	14.6	11.3	18.8
	Central Butte	Canola	26.1	28.5	30.2	30.7	24.6	60.0ab	59.7ab	75.5a	59.7ab	51.8b
		Pea	23.0c	45.6a	28.0bc	30.4bc	35.8ab	56.6ab	69.5ab	53.2b	59.0ab	77.4a
		Wheat	13.6	12.8	12.9	13.6	12.4	105.9	101.5	101.1	105.5	98.9
	Mawer	Canola	30.9a	28.3ab	33.2a	22.4b	33.2a	111.9a	94.2ab	99.7ab	83.8b	114.48a
		Pea	19.4c	30.5ab	24.5bc	35.8a	35.5a	38.5	50.1	55.7	55.3	55.35
		Wheat	7.8	7.1	7.9	7.9	8.8	49.8	42.8	52.3	51.7	57.76

† Treatments labelled F(25), F(50) and F(100) and C denote 75% applied as seed-placed and 25% applied as foliar, 50% P applied as seed-placed and 50% as foliar, and 100% P applied as foliar, and unfertilized control respectively.

‡ Means were separated using Tukey's HSD. Means with same letter within same crop, site and year are not significantly different (α=0.10).

§ No letters denotes no significant differences (α=0.10).

Table B.3: St. Brieux 2016 foliar P wheat grain and straw yield, P uptake and Zn and Fe content (salvaged). Canola and pea completely lost to flooding.

Treatment	Variable					
	Straw P	Grain P	Straw Yield	Grain Yield	Grain Zn	Grain Fe
	———————————————kg ha^{-1}—————————————				mg kg^{-1}	mg kg^{-1}
C	3.1	13.3	4098	2422	9.7	15.9
SP	2.1	11.6	5259	2426	8.7	25.2
F(25)	2.7	12.1	3563	1702	6.8	41.2
F(50)	2.8	12.8	3878	2167	7.8	18.4
F(100)	2.8	12.4	4008	2342	7.0	184.7

† Treatments labelled C, SP, F(25), F(50) and F(100) denote unfertilized control, all (100%) seed placed P, 75% applied as seed-placed and 25% applied as foliar, 50% P applied as seed-placed and 50% as foliar, and 100% P applied as foliar respectively. All fertilized treatments received a total of 20 kg P_2O_5 ha-1.

Table B.4: Fall soil nitrate analysis of 2016 and 2017 foliar P field sites.

Crop	Depth (cm)	Treatment†	NO_3 (kg N ha^{-1})						
			Pilger 2016	Central Butte 2016	Rosetown 2016	St. Brieux 2016	Pilger 2017	Central Butte 2017	Mawer 2017
Canola	0-15	C	12.5	6.6	9.1	x	12.7	10.6	5.4
		SP	14.5	6.4	7.1	x	7.5	33.4	5.2
		F(25)	10.8	5.2	4.8	x	7.4	10.5	2.2
		F(50)	11.3	5.8	6.8	x	8.6	9.8	3.8
		F(100)	12.2	6.3	7.9	x	17.9	14.4	4.1
	15-60	C	5	3.5	3.9	x	4.8	1.9	4.2
		SP	5.3	3.4	4.7	x	4.1	1.6	2.7
		F(25)	3.6	3.8	3.1	x	3.3	1.5	10.4
		F(50)	4.9	3.9	3.7	x	3.6	1.5	2.5
		F(100)	5.6	3.4	4.0	x	4.0	1.8	3.3
Pea	0-15	C	9.4	7.0	17.0	x	7.2	9.0	8.6
		SP	7.9	10.1	21.6	x	5.2	10.5	10.9
		F(25)	8.9	7.6	15.3	x	6.9	14.0	8.2
		F(50)	11.4	6.7	15.7	x	5.8	9.9	11.4
		F(100)	8.8	8.5	9.1	x	5.9	11.8	6.3
	15-60	C	4.7	3.5	3.9	x	3.2	2.1	2.5
		SP	3.3	4.6	4.9	x	3.9	1.7	2.9
		F(25)	3.3	3.6	4.2	x	2.6	2.1	2.1
		F(50)	4.9	3.9	4.2	x	2.4	1.9	2.6
		F(100)	4.8	3.7	3.5	x	2.3	2.2	2.4
Wheat	0-15	C	12.6	9.8	8.3	16.7	8.2	26.9	14.3
		SP	10.7	10.3	8.1	12.5	10.3	15.2	21.6
		F(25)	13.7	7.0	9.7	14.0	10.9	20.7	18.0

	F(50)	11.1	7.5	7.9	19.6	8.7	27.8	13.4
	F(100)	8.9	7.8	9.0	18.8	12.9	11.1	31.7
15-60	C	4.5	10.1	4.6	6.9	2.1	4.2	9.9
	SP	5.5	4.2	3.2	5.3	2.7	1.5	23.0
	F(25)	4.8	3.5	3.9	7.0	4.0	2.8	4.9
	F(50)	4.0	3.3	2.8	8.2	2.9	3.4	2.8
	F(100)	4.1	5.4	3.2	8.1	1.9	3.9	22.4

† Treatments labelled F(25), F(50) and F(100) and C denote 75% applied as seed-placed and 25% applied as foliar, 50% P applied as seed-placed and 50% as foliar, and 100% P applied as foliar, and unfertilized control respectively.

Table B.5: Outliers detected by Grubbs test in crop response to foliar P fertilization field trials in 2016. Treatments with an outlier detected are displayed with a number value.

Site	Paramter	Crop	C †	SP	F(25)	F(50)	F(100)
Pilger	Grain N	Pea	-	-	-	-	115.4
	Grain P	Canola	-	-	2.1	-	-
		Pea	-	-	-	-	11.0
	Grain Fe	Pea	-	-	1.4	-	1.0
		Wheat	-	-	-	0.2	-
	Grain Zn	Pea	-	-	0.1	-	-
	Straw N	Canola	27.1	30.8	-	-	-
		Pea	-	-	-	-	22.6
	Straw P	Canola	2.5	4.2	2.1	-	-
		Pea			3.4	-	-
Central Butte	Grain N	-	-	-	-	-	-
	Grain P	Canola	-	-	-	7.7	-
	Grain Fe	Pea	-	-	-	0.9	-
	Grain Zn	Pea	-	0.2	-	-	-
	Straw N	Canola	-	-	3.2	-	-
		Pea	-	-	12.9	-	-
	Straw P	Wheat	1.6	-	-	2.6	
Rosetown	Grain N	Canola	162.1	-	-	-	-
	Grain P	Canola	34.5	34.1	-	-	-
	Grain Fe	Pea	-	1.1	-	-	-
		Wheat	1.1	-	-	0.1	
	Grain Zn	Wheat	-	-	0.1	-	-
	Straw N	Canola	-	-	13.1	-	-
	Straw P	Canola	-	-	3.4	-	-

† Treatments labelled F(25), F(50) and F(100) and C denote 75% applied as seed-placed and 25% applied as foliar, 50% P applied as seed-placed and 50% as foliar, and 100% P applied as foliar, and unfertilized control respectively.